VOLUME 1 OF 2

THE LADY LORETTA FORMATION : SEDIMENTOLOGY AND STRATIFORM SEDIMENT-HOSTED BASE METAL MINERALISATION

JOHN N DUNSTER

Bachelor of Applied Science (Biology)

Bachelor of Science (Hons) (Geology)

Master of Science (Geology)

This thesis was submitted for the degree of Doctor of Philosophy

at the Centre for Ore Deposit and Exploration Studies,

Special Research Centre,

Geology Department, University of Tasmania.

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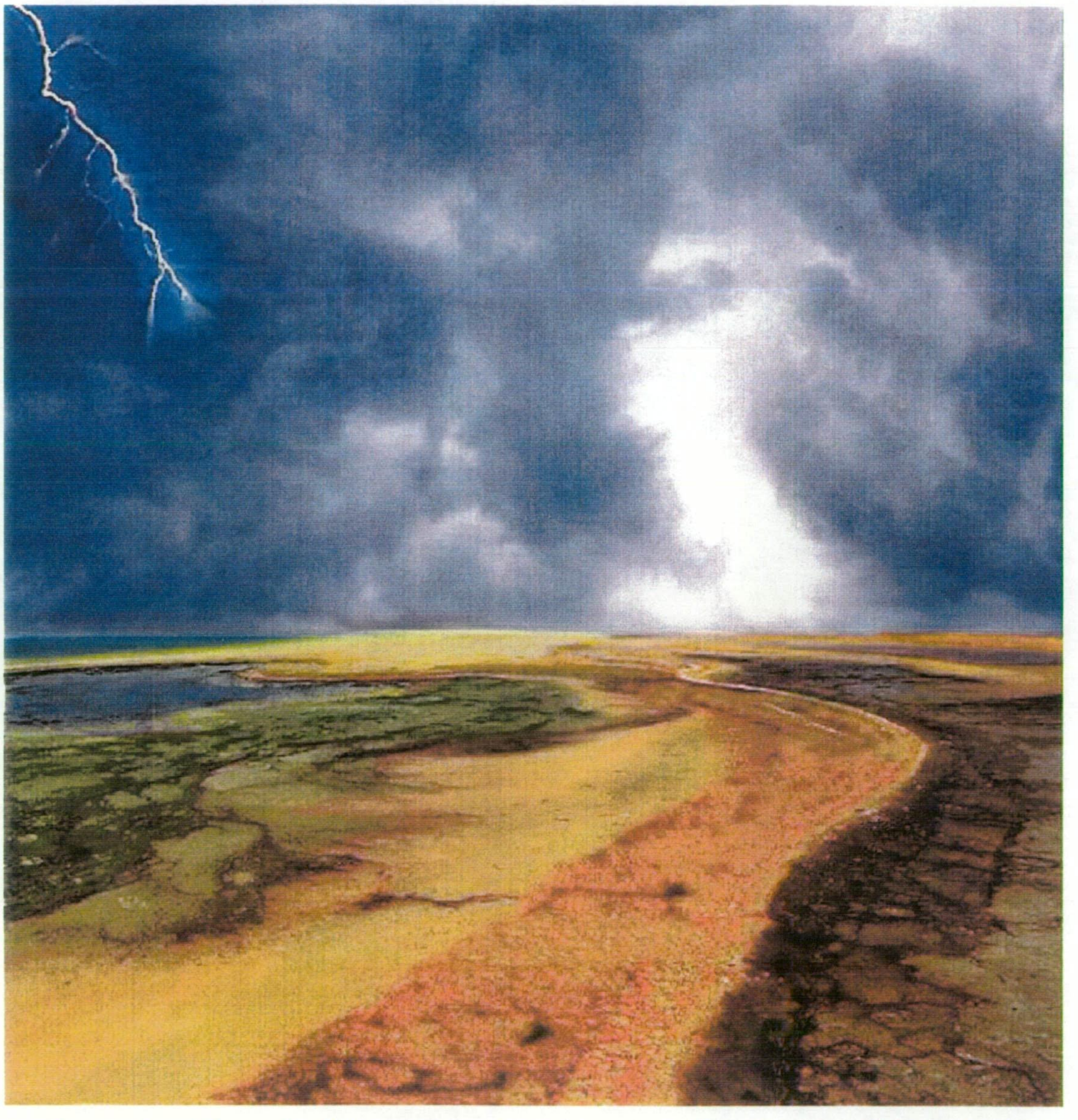
July 1997



Frontispiece: The author's impression of a storm approaching the edge of the Lady Loretta Lagoon ca. 1647 Ma, looking to the southeast from what is now gridline 2420N.

DECLARATION AND AUTHORITY OF ACCESS

This thesis contains the results of three years research undertaken at the CODES Key Centre, University of Tasmania, between April 1994 and July 1997.

The author acknowledges that:

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ABSTRACT

The Palaeoproterozoic Lady Loretta Formation of the Mount Isa Basin, northwestern Queensland, was deposited during a series of fluctuations in relative sealevel that constitute an overall regression. The interpreted sedimentary environments range from sub-wavebase to supratidal. Carbonaceous lagoonal sediments host economic stratiform base metal mineralisation.

Previous tectono-sedimentary models for the Lady Loretta Formation that invoked a rift-setting and interpreted a regional "basal breccia" as evidence of syn-sedimentary uplift and erosion are disputed. This study interprets the setting as a ramp/shelf with no evidence of large-scale syn-sedimentary tectonic activity. The "basal breccia" is interpreted as a duricrust that has no palaeoenvironmental implications for the depositional setting.

Sedimentary structures, microbialites (stromatolites), evaporite pseudomorphs and the arrangement of interpreted depositional environments indicate fluctuations in water depth, tidal influence and storm activity during the deposition of the Lady Loretta Formation. Shale, laminated to massive argillaceous dolostone and fine grained sandstone containing hummocky and swaley cross-stratification are interpreted as the deepest-water facies present. Shallow marine carbonates now consist of variably silicified dolostone and include microbialites that range from prone mat to biostromes and bioherms of domal, digitate and columnar forms with significant synoptic relief. Ooid shoals developed in areas of shallow agitated water. Widespread mixed carbonate/siliciclastics and carbonates in the northern outcrops of the Lady Loretta Formation appear to be cyclic and developed as a facies mosaic. They are interpreted as peritidal on the basis of bipolar-bimodal palaeocurrent directions and the prevalence of flaser to lenticular bedded units, tidal rhythmites, interference wave ripples and herringbone cross-stratification with reactivation surfaces. Storm deposits such as imbricated plate breccias and gutter casts are common. Widespread casts and moulds of halite and pseudomorphs of discoidal gypsum, enterolithic anhydrite and cauliflower cherts are interpreted to represent an evaporitic overprint produced during regression when a marine sabkha developed locally. Associated sedimentary features include desiccation cracks, synaeresis cracks, washout rills, scour pits and wrinklemarks.

Highly carbonaceous pyritic shale, variably diagenetically altered Fe- and Mn-rich carbonates and dolomitic siltstone were deposited in isolated areas, laterally and stratigraphically associated with tidal and possible subaerial facies. These pyritic facies occur at several localities in the Lady Loretta Formation, one of which hosts the Lady Loretta ore body consisting of 8.3 Mt of 12% Zn-Pb-Ag combined. The ore and its host rocks contain a variety of microbialites, including silicified or pyritised prone mat and low-relief, small diameter, elongate and inclined digitate forms. Parts of the host sequence also contain wave ripples, crossbeds with bipolar palaeocurrent directions and a possible sulphate evaporite overprint. Sulphur isotope data for pyrite and base metal sulphides are interpreted to indicate a closed system with abundant microbial sulphate reduction. Collectively, this is

interpreted to indicate that the host rocks were deposited in a restricted lagoon developed within a regional tidal-flat environment.

Similar potential host lithologies are recognisable elsewhere in the formation by their sedimentary features, the high Mn and Fe content of the carbonate and the abundant bedded pyrite interpreted to have originally been prone microbial mat. Theoretically, the distribution of such lagoonal facies can be predicted by sequence stratigraphy. On a rimmed shelf, extensive lagoonal facies can develop during a lowstand as the barrier becomes exposed by falling sealevel. Smaller perched lagoons may develop on the tidal flat of an unrimmed shelf. In highstand systems tracts on a rimmed shelf, microbialite growth may keep pace with rising sealevel to create large lagoons during minor regressions. Sub-wavebase shales that correspond to maximum flooding surfaces also have the potential to host base metal mineralisation in the Lady Loretta Formation.

Previously proposed genetic mineralisation models for the Lady Loretta ore body have been revised based on the new interpretation of the deposition setting. The classic SEDEX model that relies on exhalation into deep anoxic water confined within a graben is untenable in the shallow lagoonal setting proposed herein. A new model in which mineralisation is interpreted to have formed in unconsolidated sediments in the shallow subsurface is based on geochemical, isotopic and textural data. It is also consistent with a lagoonal setting where carbonaceous and pyritic sediments would act as reductants. Alternatively, a late epigenetic model involving the long distance migration of brines and mineralisation by replacement of, or void-fill in, consolidated rock is supported by the difference between the SHRIMP U-Pb zircon age of a tuff in the footwall of the host sediments (1647±4 Ma) and the Pb isotopic model age of the mineralisation (within range of 1600 - 1570 Ma).

Comparison of the geochemistry of the ore sequence with other carbonaceous pyritic packages elsewhere in the formation suggests that geochemical exploration should be directed towards the direct detection of metals and pathfinder elements such as Ba, Cd, Hg and Tl, and the use of alteration indices and carbon and oxygen stable isotopes to map haloes.

KEYWORDS

Carbon isotopes, cyclicity, base metal, duricrust, evaporites, geochemistry, Lady Loretta Formation, lagoon, microbialites, mineralisation, ooids, oxygen isotopes, palaeocurrents, Palaeoproterozoic, pathfinder elements, pisoids, ripples, sedimentology, Statherian, storm deposits, stratigraphy, tidalites.

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SPECIALIST SOFTWARE ACKNOWLEDGMENTS

Geological Trigonometry

‡GeoTrig 3.0 (RockWare Utilities, 1996)

Graphic Logs

‡AppleCore 0.7 (Ranger, 1996)

Fischer Plots

Custom written template for Excel 7.0

Markov Analysis

Markov1 custom written in BASIC

Markov2 written in BASIC based on (Wells, 1989)

Palaeocurrent Analysis

‡Rose 1.0 (Thompson & Thompson, 1993)

‡WinRose R0.9 - Crossbed (Krumm & Peterek, 1996)

Spectral Analysis

‡DPLOT95 V1.2.0.5 (US Army Engineers, Waterways Experiment Station)

LabWindows CVI (National Instruments)

Stereo-Plots

‡QuickPlot (van Everdingen & van Gool, 1990)

‡StereoNet Light 3.03 (Geological Software, Norway, 1995)

Ternary Plots

‡Triplot 2.0 (Braedke, 1993)

Digital Art

PhotoStudio SE (ArcSoft, 1994-1995)

‡Graphics Factory 1.0, (Kamyan Software, 1996)

‡ Those so-marked can be located via. the Internet.

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LIST OF ABBREVIATIONS AND ACRONYMS

AAS	atomic absorption spectrophotometer
AGSO	Australian Geological Survey Organisation (formerly BMR)
AMIRA	Australian Mineral Industries Research Association Limited
ARC	Australian Research Co-operative
ATP	authority to prospect
BCC	Brenda Creek Composite Field Section
BIF	banded iron formation
BLB	Bloodwood Bore Field Section
BMR	Bureau of Mineral Resources (now AGSO)
CAR	Carrier area
CCC	Cartridge Creek Composite Field section
CAT	Cattle Creek area
CEC	Carpentaria Exploration Company
CODES	Centre for Ore Deposit and Exploration Studies, Special Research Centre, University of Tasmania
CRA	CRA Exploration (now Rio Tinto)
d	diameter
DCR	diagenetic crystallisation rhythmites
d.f.	degrees of freedom (statistics)
dup.	duplicate
ED	east decline drillhole
EI	east inclined drillhole
EM	electro-magnetics
est.	estimated
eq.	equivalent
FU	fining up
g/t	gram per tonne
Ga	10^9 years
GLS	Greater Loretta Syncline Field Section
GPS	global positioning system
GSQ	Geological Survey of Queensland
GUB	Gundaria Bore Field section
HCS	hummocky cross-strata
HYC	Here's Your Chance (McArthur River ore body)
INC	Inca Creek area
IP	induced polarisation
IR	insoluble residue
JOC	Johnson Creek area
KD1-6	Kamarga Dome Field Sections
L3C	Line 3 Costean, Lady Loretta ore body
lam.	laminated
LLD	Lady Loretta ore body (sample locations)
LLG	Lily Lagoon Composite Field Section
LST	lowstand system tract
Ma	10^6 years
MEP	Mellish Park Field Section
MET	metallurgical drillhole
MFS	maximum flooding surface
ML	mining lease
Mt	10^6 tonnes
MVT	Mississippi Valley-type (ore body)
n	number (of samples)
NA	not applicable
NABRE	North Australian Basins Resource Evaluation
NC	not calculated
ND	not determined
NT	Northern Territory
NTGS	Northern Territory Geological Survey
OGR	Ogilive Range area
P	probability
Pancon	Pancontinental Mining Limited

PESA	Petroleum Exploration Society of Australia
PHP	Phosphate Plant Field Section
PMA	Ploughed Mountain
P_{ml}	Lady Loretta Formation map symbol
P_{ms}	Shady Bore Quartzite map symbol
P_{mz}	Esperanza Formation map symbol
POC	Police Creek Field Section
PS	polished slab
ppm	parts per million
QDME	Queensland Department of Mines and Energy
QLD	Queensland
r^2	regression coefficient
RAB	rotary air-blast drilling
REC	Redie Creek Composite Field Section
Renison	Renison Goldfields Consolidated Group
RI	ripple index (= vertical form index)
RL	relative level
Ro	reflectance
RSI	ripple symmetry index
RSL	relative sealevel
RUC	Russell Creek Field Section
SA	South Australia
SCS	swaley cross-stratification
SEDEX	sedimentary exhalative
SER	Seymour River area
SHRIMP	sensitive high-resolution ion microprobe
SI	ripple straightness index
SPOT	Satellite Probatoire pour l'Observation de la Terre
SSHBM	stratiform sediment-hosted base metal
TD	total depth
THR	Thornton River Field Section
TOC	total organic carbon
TRE	Trent Composite Field Section
TS	thin section
tst	true stratigraphic thickness
TST	transgressive system tract
U/G	underground
VHMS	volcanic-hosted massive sulphide
VPDB	Vienna Peedee Belemnite isotopic standard
VSMOW	Vienna Standard Mean Ocean Water carbon and oxygen isotopic standard
WA	Western Australia
WAN	Wangunda Bore Field Section
WD	west decline drillhole
WI	west incline drillhole
XRD	x-ray diffraction
Z	Z score (statistics)
δ	delta (difference - isotopes)
η	eta (ripple height)
λ	lambda (ripple wavelength)
μ	mu (mean)
σ	sigma (standard deviation)
χ	chi (statistics)
‰	parts per thousand

PREFACE

This thesis concentrates on the sedimentology of the Lady Loretta Formation, comparing the depositional setting of host rocks of the Lady Loretta ore body to the formation regionally and considers this as a potential controlling factor for base metal mineralisation. This study also provides new insights into the tectono-sedimentary setting, litho- and sequence stratigraphy, quantitative and cyclostratigraphy, local structural geology, geochemistry, diagenesis and genetic models of mineralisation. Such an eclectic mix necessitated a more general approach than is traditional in purely sedimentological studies. However, the successful integration demonstrates the power of the approach and enabled the development of a new conceptual exploration framework.

This work was concurrent with two major studies to which I have contributed:

- the AMIRA/ARC P384 study of the northern Australian Proterozoic stratiform sediment-hosted ore bodies, conducted by researchers at CODES. The AMIRA project resulted in a new genetic model for the Lady Loretta ore body. Critiques of that and other possible models are included in this thesis

- a regional basins study (NABRE) initiated by AGSO in 1995. A sequence stratigraphic approach, utilising gamma logs of outcrop and drillcore, provided the basin-scale framework for my study.

The first four introductory chapters of the thesis describe this, and previous studies, the temporal and global setting, the basinal, stratigraphic and structural setting and the mineralogy and isotope geochemistry. Chapters 5 to 9 document and interpret key sedimentary features, microbialites and evaporites. Many of these are recorded for the first time in the Lady Loretta Formation. Chapter 10 ties all this together into a new sedimentary model. Diagenesis and surficial processes are described in Chapters 11 and 12, with an emphasis on the implications for exploration geochemistry and the mineralisation process. The latter is dealt with in Chapter 13 which examines the Lady Loretta ore body but also considers sub-economic mineralisation away from the mine and evaluates potential genetic models. The significant exploration implications are discussed in Chapter 14. Chapter 15 is an overall synthesis. The final, short, chapter is an attempt to put the Ph into a PhD.

Details of methodology, quantitative and analytical studies and the graphic logs are presented as Appendices.

A number of papers have already arisen from this thesis. Those citations marked with an asterisk in the text are included in Appendix A-14. In the case of those peripheral to the main topic of the thesis, only a precis of this material has been included in the body of the thesis. Those cited as "in press" have been refereed and accepted for publication.

Chapter 1 - Introduction

1. INTRODUCTION

1.1 SIGNIFICANCE OF THE LADY LORETTA FORMATION AND THE LADY LORETTA ORE BODY

The Lady Loretta Formation is one of several north Australian Palaeo- and Mesoproterozoic formations that contain significant stratiform sediment-hosted base metal (SSHBM) ore bodies. The Lady Loretta ore body is a single 40 m thick lens of 8.3 Mt Zn-Pb-Ag using a 12% Zn equivalent cut-off[†] (Hancock and Purvis, 1990). The lower 5-10 m is extremely high grade, commonly having in excess of 50 wt% Zn + Pb.

The Lady Loretta host rocks and ore are superficially similar to those of other SSHBM ore bodies and many previous workers have inferred similar environments of deposition and genetic models of mineralisation. However, both these issues remain controversial, even in the better studied examples at Mount Isa and HYC. Models of SSHBM mineralisation range from syngenetic at the sediment/water interface to late epigenetic syn-deformational. The host sediments from similar ore bodies have been variously interpreted as anoxic deep marine, shallow marine, deep or shallow lacustrine and sabkha.

Little previous work has been done on the sedimentology of the Lady Loretta Formation regionally and almost nothing was known of the sedimentology in the vicinity of the Lady Loretta ore body.

The core drilling undertaken in the ore body, including extensive underground drilling that was not available to most previous workers, has been combined with core and RAB drilling by other exploration companies, new geochemical data and outcrop studies to postulate detailed sedimentological and diagenetic models. These form an intrinsic part of any genetic model for mineralisation. Indeed, the palaeo- water depth is pivotal to the most recently proposed model (McGoldrick *et al.*, 1996) and diagenetic studies are important to establish the relative timing of mineralisation. Some aspects are unique to the Lady Loretta ore body, but the model has implications for the interpretation of other known ore bodies and can be applied to the search for new SSHBM deposits.

1.2 AIMS OF THIS STUDY

The aims of this study and the specific problems it addresses are:

- to elucidate the regional depositional history of the Lady Loretta Formation and compare this to the environment of deposition of the host rocks of the Lady Loretta ore body,

  - was the regional setting marine or lacustrine, did water depths vary significantly and in what way?

  - what was the environment of deposition of the host sediments?

[†] *Unless specified otherwise, Lady Loretta "ore" is defined as >12 wt% 1.0Zn + 0.4Pb + 0.02Ag.*

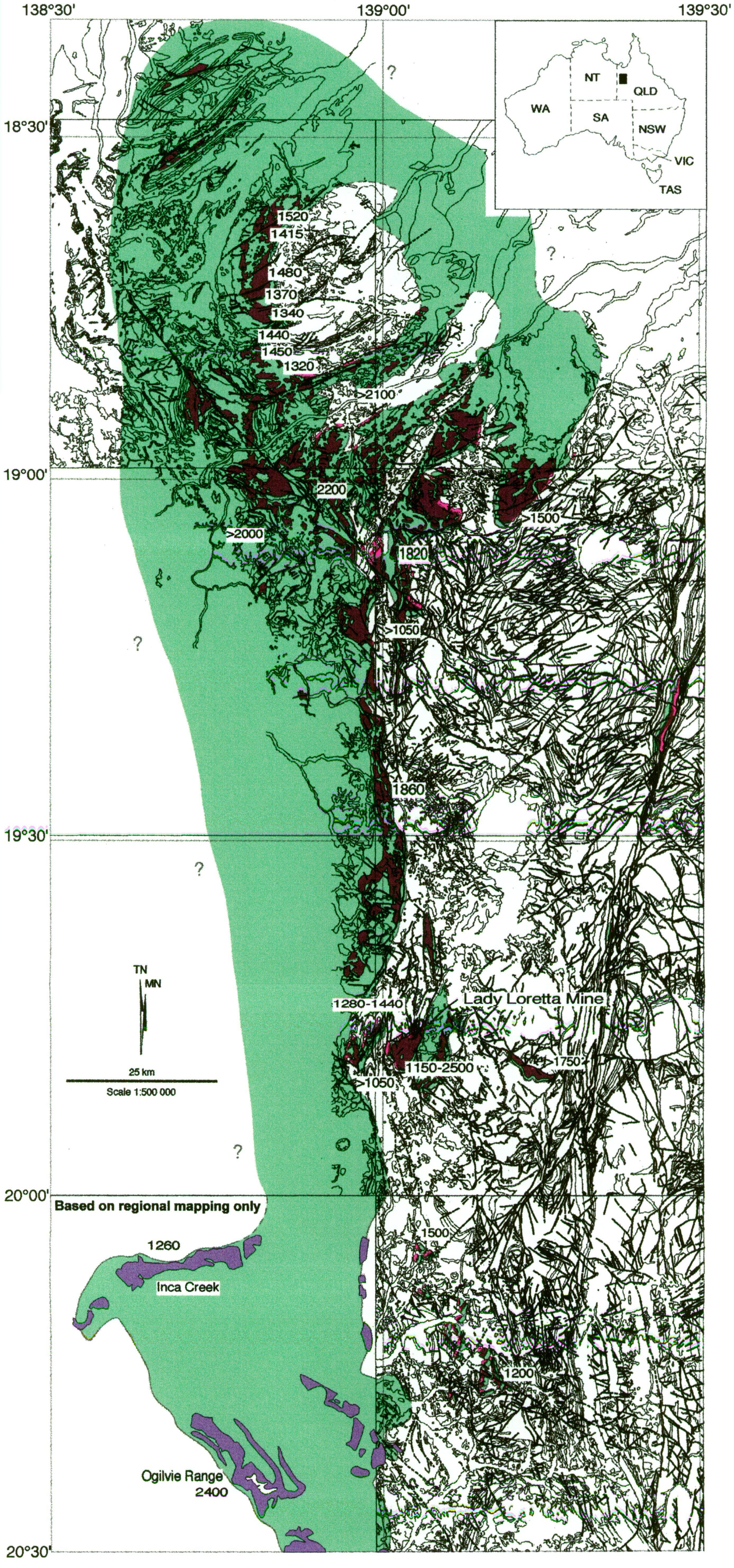
- do the highly carbonaceous and pyritic rocks that host the ore occur elsewhere in the Lady Loretta Formation and is their distribution predictable?

- determine the tectono-sedimentary setting of the Lady Loretta ore body,
  - what is the most appropriate basin model?
  - were the host sediments to the ore body deposited in a syn-sedimentary graben as proposed by previous workers?
  - is there any evidence of syn-sedimentary fault activity and did such faults act as conduits for mineralising fluids at the ore body?
  - is the "basal breccia" to the Lady Loretta Formation evidence of intraformational regional uplift and why is it commonly anomalous in metals?
- determine the regional diagenetic history of the unit and relate the mineralisation to the regional diagenesis, especially with respect to timing,
  - is the diagenesis at the ore body any different to the formation regionally?
  - can the overall diagenetic sequence be used to establish the relative timing of base metal paragenesis?
- compare the Lady Loretta ore body to other similar mineralisation in northern Australia,
  - review sub-economic SSHBM mineralisation in the Lady Loretta Formation away from the ore body
  - briefly compare the Lady Loretta ore body with the interpreted sedimentary settings and mineralisation models of other major SSHBM ore bodies in northern Australia
- assist in constraining a genetic model, based on Lady Loretta, that can be used in exploration,
  - review possible genetic models for the Lady Loretta SSHBM mineralisation and discuss the most appropriate
  - propose appropriate empirical exploration techniques.

1.3 LOCATION, VEGETATION, PHYSIOGRAPHY AND ACCESS

The Lady Loretta Formation can be recognised as outcrop or inferred as subcrop over an area of >3500 km^2 in central northwestern Queensland, Australia (Figure 1-1). Elevated lateritic plains and dissected ridges form low to moderate (70 m) relief over areas of outcrop. Most of the area is open woodland or grassland typified by *Eucalyptus brevifolia* (snappy gum), *Acacia shirleyi* (lancewood) and *Triodia pungens* (spinifex). *Acacia shirleyi* is common on the ferruginous ridges, especially so around the Lady Loretta ore body. The geo-botantical indicators *Polycarpaea spirostytis*, *P. glabra* (commonly interchangeably called copper or zinc weed) and *Jacksonia ramosissima* occurs sporadically throughout the best-drained acid soils developed on the Lady Loretta Formation. *Eriachne mucronata* and *Tephrosia sp.* are considered indicator species at both the Dugald River and Lady Loretta ore bodies (Cole, 1977, 1980).

Figure 1-1 (fold-out): Probable present extent of outcrop, subcrop and thickness of the Lady Loretta Formation modified from published maps and showing thicknesses calculated during this study. No depositional edge has been identified. The western extent of the formation is unknown because of Cambrian cover. In the north, the Lady Loretta Formation is covered by younger Proterozoic sedimentary rocks.



138°30'
139°00'
139°30'
18°30'
19°00'
19°30'
20°00'
20°30'
NT
QLD
WA
SA
NSW
VIC
TAS
1520
1415
1480
1370
1340
1440
1450
1320
>2100
2200
>2000
>1500
1820
>1050
1860
1280-1440
Lady Loretta Mine
1150-2500
>1750
>1050
TN
MN
25 km
Scale 1:500 000
Based on regional mapping only
1260
Inca Creek
1500
1200
Ogilvie Range
2400

The climate is semi-arid, comprising a short humid summer wet season and a long dry winter. Summer maximum temperatures often exceed 40°C and winter minima can be below 5°C.

This area is very sparsely populated and the main land use is cattle grazing. The logistic centre is the mining town of Mount Isa. It is connected to surrounding towns by the only sealed road, the Barkly Highway. Access to the Lady Loretta mine is along the Barkly Highway 65 km northwest of Mount Isa, then north along the unformed McNamara's Road for 75 km. The unsealed Camooweal Development Road provides access to outcrops further north. Other areas are accessible along fourwheel drive tracks cleared by graziers or mining companies involved in exploration; but final access to most outcrops visited during this study was on foot. All ground-access is restricted by widespread flooding during the wet season.

1.4 ECONOMIC GEOLOGY OF THE REGION

1.4.1 Introduction

The Proterozoic rocks of northwest Queensland and the northeastern Northern Territory are prospective for a wide variety of commodities ranging from gold to petroleum. However, the province is best known for its Zn-Pb-Ag mines and is considered to be one of the major metallogenic provinces of the world (Eriksson and Chuck, 1985).

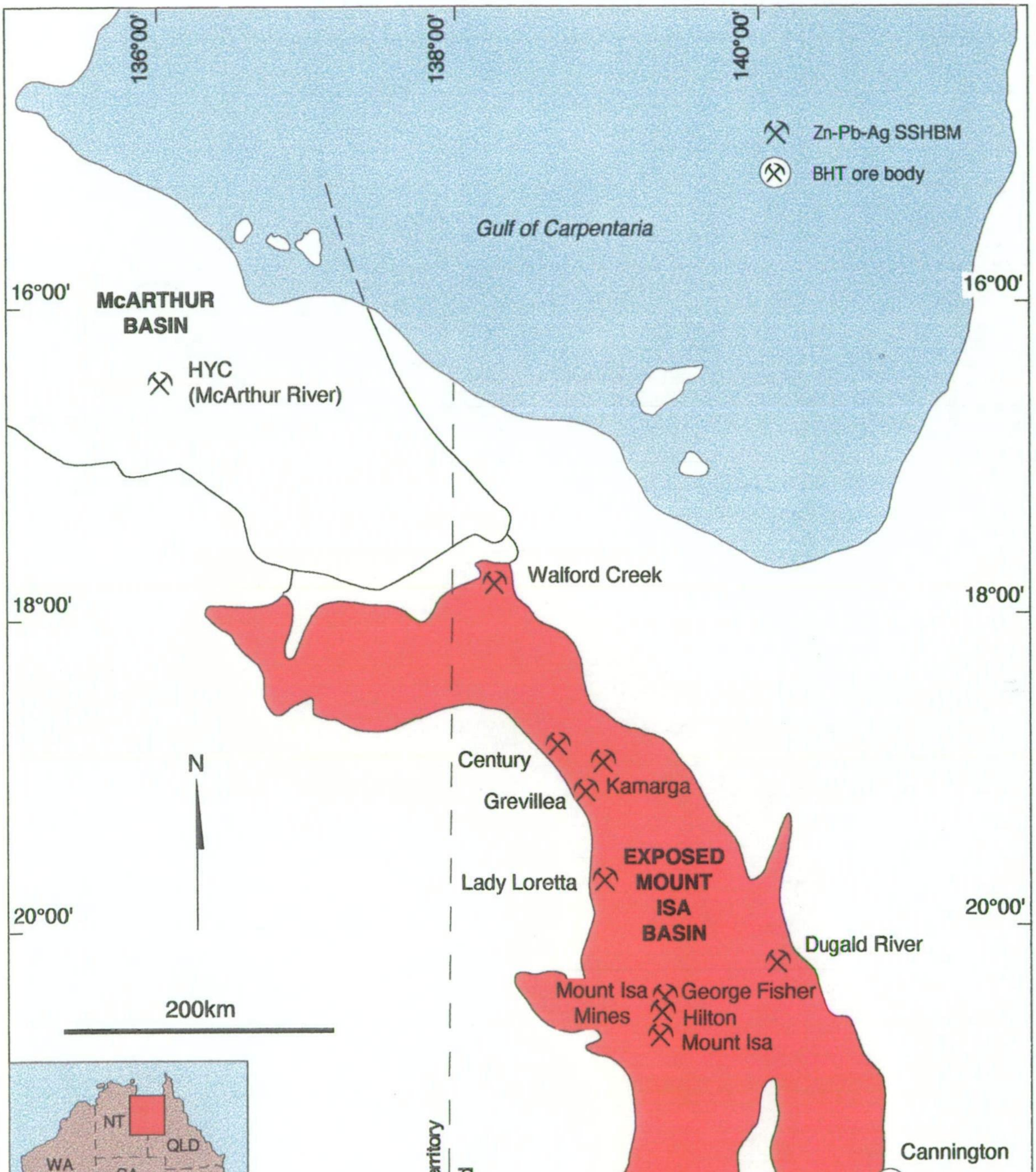
1.4.2 The Northern Australian Zinc Belt

The province of Proterozoic rocks extending southeast of Mount Isa, Queensland, and northwest into the Northern Territory contains several of the world's largest SSHBM ore bodies and dozens of subeconomic prospects. Mount Isa mine, Hilton, George Fisher (Hilton North), Dugald River, Lady Loretta, Century and McArthur River (HYC) all lie within this belt of zinc mineralisation. Figure 1-2 and Table 1-1 show the location of these major ore bodies and their estimated reserves.

ORE BODY	RESERVES				REFERENCE
	Mt	%Zn	%Pb	g/t Ag	
Century	118	10.2	1.5	36	Walthro & Andrews, 1993
Lady Loretta	8.3	18.4	8.5	125	Hancock & Purvis, 1990
Dugald River	38	13.2	2.1	32	Sheppard & Main, 1990
Mount Isa	150	7	6	150	Forrestal, 1990
Hilton	50	9	6.5	150	Forrestal, 1990
McArthur River	104	14.1	6.1	60	Logan *et al.*, 1990

Table 1-1: Pre-mining reserves for north Queensland SSHBM ore bodies. Note the lower tonnage but higher grade cut-offs quoted for Lady Loretta.

Figure 1-2: Location of the major stratiform, sediment-hosted base metal ore bodies in the north Australian zinc belt.



136°00'
138°00'
140°00'
Zn-Pb-Ag SSHBM
BHT ore body
Gulf of Carpentaria
16°00'
16°00'
McARTHUR
BASIN
HYC
(McArthur River)
Walford Creek
18°00'
18°00'
Century
Kamarga
Grevillea
N
EXPOSED
MOUNT
ISA
BASIN
Lady Loretta
20°00'
20°00'
Dugald River
Mount Isa
Mines
George Fisher
Hilton
Mount Isa
200km
NT
QLD
WA
SA
NSW
VIC
TAS
Northern Territory
Queensland
Cannington
Pegmont

1.4.3 Other Mineralisation

The Proterozoic rocks of the province contain numerous other ore bodies including Broken Hill-type mineralisation at Cannington, brecciated sediment-hosted Pb-Zn-Ag at Silver King, U at Mary Kathleen, Au at Ernest Henry, Cu-Au at Starra, epigenetic Cu at Mount Isa, Mammoth Mines, Mount Oxide and Lady Annie. The Cu mineralisation at Lady Annie is two kilometres from Lady Loretta and is hosted by an older stratigraphic unit. Although there does not appear to be a genetic relationship between the two styles of mineralisation, their proximity and common ownership undoubtedly enhances their economic viability.

Overviews of the mineralisation of the province and details of the major ore bodies are given in Hughes (1990), Laing (1996) and Solomon and Groves (1994).

Apart from the Zn-Pb-Ag mineralisation, the Lady Loretta Formation regionally is host to several silica-flood and fault-related brecciated sediment-hosted Cu prospects. The most significant are Lvov, Big Ben, Galah Syncline, Busy Bee and Drifter. Details are given in van Dijk (1991).

1.4.4 PETROLEUM PROSPECTIVITY

Proterozoic oil has been recovered from the Northern Territory and many of the SSHBM ore bodies in both the Northern Territory and Queensland contain hydrocarbons ranging from live oil to meta-bitumen. Petroleum exploration in Queensland has focused on the northern-most Palaeo- and Mesoproterozoic sequences which range from thermally immature, through oil and gas-prone, to overmature. Work by Amoco (Dorrins *et al.*, 1983) and Comalco (McConachie, 1993a) identified thick sequences of source rock and suitable structural traps. The Lady Loretta Formation was considered as a potential reservoir and was probably intersected in two petroleum wells (McConachie, 1993a). Oil shows were encountered in several formations, but none can be precisely correlated to the Lady Loretta Formation, which was found to be overmature for oil generation. Overall, favourable hydrocarbon maturities are confined to a relatively small area geographically and stratigraphically, and diagenesis has occluded most porosity (Dunster *et al.*, 1993 a,b).

1.5 PREVIOUS WORK AND OTHER CURRENT STUDIES

1.5.1 Discovery and Development of the Lady Loretta Ore Body

The discovery of the Lady Loretta ore body is no doubt due to its proximity to small Cu workings, two kilometres away, at Lady Annie.

While visiting Cu prospects at Lady Annie in 1938, the Queensland Government Geologist, A. K. Denmead, mapped the barite-haematite ridges that are the surface expression of the Lady Loretta Zn-Pb-Ag ore body. His samples were described as "ironstone" and did not generate any further interest. This gossan was remapped by the

BMR in 1957. However, until the late 1960s, interest continued to focus on the older rocks that host the Cu mineralisation.

During 1967-69 Placer Prospecting (Aust.) Pty Ltd undertook a re-evaluation of its joint venture Cu prospect at Lady Annie. A reconnaissance soil sampling program and IP survey conducted as part of this Cu search revealed abnormally high Pb values, in part coincident with IP anomalies, and obviously related to the gossanous horizon noted by Denmead. Placer recognised the possibility of Pb-Zn mineralisation similar to Mount Isa and the maximum lead anomaly was drilled. The hole intersected oxidised Pb-Ag mineralisation, principally anglesite and cerussite, from 50 m to the bottom of the hole at 128 m. The best grade averaged 21.2% Pb over a 7.6 m interval (Cox and Curtis, 1977). The first sulphide ore that included economic zinc grades was cored (27 drillholes later) during 1970 (Hancock and Purvis, 1990).

Drilling, surface mapping and structural analysis continued and by 1973, 69 holes totalling 24 000 m had been completed. Placer sold its interest to Mount Isa Mines Limited during 1975. Additional drilling, engineering and mining feasibility studies were carried out. Perkins (1989) documented work up to this phase. In 1985, Pancontinental Mining Limited purchased the controlling interest and formed a joint venture with Outokumpu Oy of Finland. A 4.8 m d concrete-lined exploration shaft was sunk to 468 m and 10 400 m of underground drilling were undertaken from a drive along the axis of the syncline at a depth of 336 m. A further 4000 m were drilled and bulk samples were mined prior to the completion of a feasibility study in late 1988 (Hancock and Purvis, 1990). The mine was put onto care and maintenance and the shaft allowed to fill with water. Pancontinental Mining Limited obtained 100% equity during mid 1994. During 1995, Pancontinental was taken over by Renison and in early 1996 the mine was sold to Triako whose subsidiary, Buka Minerals, became the operator. They conducted contract mining of a bulk sample during 1997.

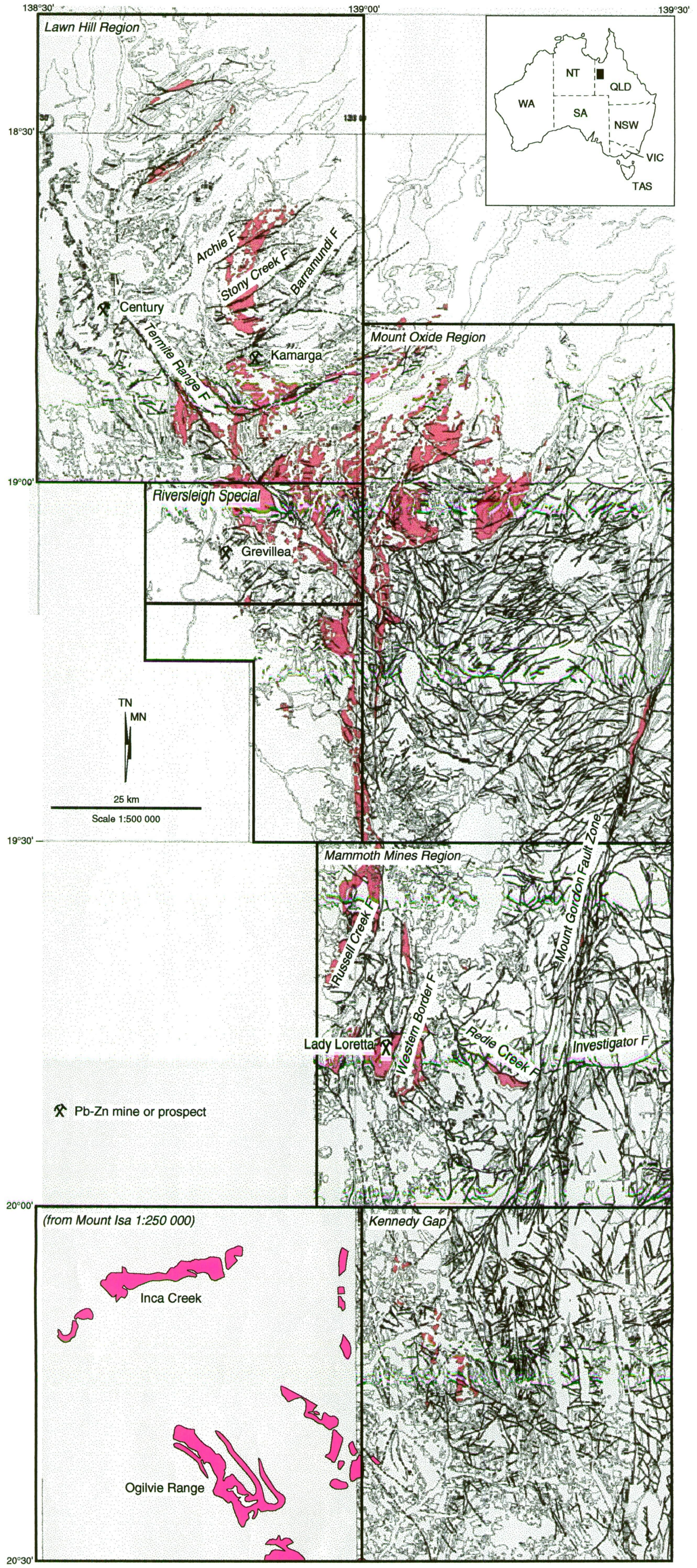
Published *in situ* reserves, using a 12% Zn eq. cut-off, are 8.3 Mt at 18.4% Zn, 8.5% Pb and 125 g/t Ag. Using a higher grade cut-off of 40% Zn eq. yields 1.0 Mt at 35.1% Zn, 18.9% Pb and 279 g/t Ag (Hancock and Purvis, 1990).

1.5.2 Previous Studies of Sedimentology, Diagenesis and Metallogeny

Regional Studies

The first information on the regional facies variation within the Lady Loretta Formation was obtained during the 1:100 000 scale mapping conducted by government agencies. The key to the published map sheets is shown in Figure 1-3. In a synthesis of this work, Hutton and Sweet (1982) described the lower Lady Loretta Formation as being deposited in a "subtidal lagoon". The host sequence to the Lady Loretta ore body was described as a local euxinic facies developed in a small sub-basin. They believed that the remainder of the formation indicated energetic intertidal and supratidal conditions. Important local variations were noted in subsequent, more detailed, papers. Cauliflower cherts in the Mammoth Mines region were taken as evidence of a hypersaline diagenetic

Figure 1-3 (fold-out): Key to the published 1:100 000 geological maps covering the area. Map sheet names are shown in italics. The mapped outcrop of the Lady Loretta Formation, the major faults and Pb-Zn ore bodies are also shown.



138°30'
139°00'
139°30'
Lawn Hill Region
18°30'
NT
QLD
WA
SA
NSW
VIC
TAS
Archie F
Stony Creek F
Barramundi F
Century
Termite Range F
Kamarga
Mount Oxide Region
19°00'
Riversleigh Special
Grevillea
TN
MN
25 km
Scale 1:500 000
19°30'
Mammoth Mines Region
Mount Gordon Fault Zone
Russell Creek F
Western Border F
Lady Loretta
Redie Creek F
Investigator F
Pb-Zn mine or prospect
20°00'
(from Mount Isa 1:250 000)
Kennedy Gap
Inca Creek
Ogilvie Range
20°30'

environment (Hutton and Wilson, 1985). Finely laminated shaly and sandy facies in the north (Mount Oxide sheet) were attributed to quieter, deeper water conditions by Hutton and Wilson (1984). They also described the eastern-most outcrops of the Lady Loretta Formation as laminated chert, red brown siltstone and fine grained sandstone. Sweet and Hutton (1980, 1982) and Hutton and Wilson (1985) speculated on the origin of the ferruginous basal breccia.

Amade (1986) drew attention to the stromatolitic facies in the Lady Loretta Formation and interpreted the formation regionally as a regression from subtidal to supratidal conditions. He assigned the host sediments of the Lady Loretta ore body to an anoxic sub-basin.

Pringle and David (1983) measured sections from the northern outcrops of the Lady Loretta Formation on the Lawn Hill sheet. Amoco (Dorrins *et al.*, 1983) undertook a regional study of the petroleum potential and drilled a series of fully-cored stratigraphic holes, including part of the Lady Loretta Formation.

Lithogeochemical exploration and drilling of the Lady Loretta Formation by Billiton was described by Beeson *et al.* (1989). They noted locally significant diagenetic K feldspar enrichment and used alkali element compositions to “distinguish the sediments of the mineralised shallow-emergent locations from both those of more permanent water cover (lacustrine or lagoonal), and from those close to basin margins”.

Comalco (McConachie, 1993) undertook reconnaissance mapping, recorded seismic and drilled petroleum wells that are useful for lithostratigraphic correlation, sequence stratigraphic interpretation and basin analysis.

These data have all been incorporated into the present study and the location and significance of key drillholes are described more fully in Chapter 3.

Previous Inferences about the Sedimentology and Metallogenesis of the Lady Loretta Ore Sequence

Early unpublished technical reports and the first published papers on the Lady Loretta ore body, by Alcock and Lee (1974) and Loudon *et al.* (1975), concentrated on the surface geochemistry and structural geology and did not deal with the sedimentology. After Lee (1972) interpreted inwardly-directed syn-sedimentary slumps in and around the mine, a separate deep-water sub-basin was invoked. This interpretation was supported by the description of the host sediments as turbidites, and the thousands of bands of pyrite throughout the Lady Loretta Formation at the mine were interpreted as a product of the mineralising fluids.

Russell *et al.* (1976) expressed a dissenting view. They interpreted the ore host sediments as having been deposited in a higher energy environment than the footwall or hanging wall; favouring a shallow lagoonal setting and invoking a possible biological origin for at least some of the bedded pyrite. They also interpreted a palaeo-high of exposed pre-McNamara Group rocks directly north of the present ore body.

D. E. Large (1980) included a discussion of the Lady Loretta ore body in his major work on SEDEX deposits. He considered that the ore was formed by exhalation into deep water contained in half-graben (corresponding to the present Loretta Syncline) within a larger rift (Dunnet's (1976) Paradise Rift). This was the first published genetic model and it influenced much of the subsequent work.

Carr (1981) undertook a major study of the mineralogy, petrology and geochemistry of the host rocks of the Lady Loretta ore. His sedimentological data were confined to the mine and were collected pre-underground drilling. On the basis of this limited information, he argued that the footwall dolomitic unit was deposited in less that 10 m of water. The Ore Sequence sediments were interpreted as deeper, but still less than 100 m to 200 m. Cyclic sedimentation in the hanging wall, originally interpreted to be of deep water, turbidite origin, was reinterpreted as relatively shallow water sedimentation. Carr (1981) cited evidence of syn-sedimentary faulting which he considered to be responsible for the inter-ore breccias and a feeder for mineralising fluids.

During 1983, Muir published a synthesis of the depositional environments of the host rocks to the northern Australian Pb-Zn ore bodies. At that time, there was little publicly available information on the Lady Loretta ore, however she noted that "the mineralised siltstones are associated with dolomites containing evaporite pseudomorphs, stromatolitic dolomites, dolarenites and carbonaceous siltstones and shales." Williams (1980) described the lithostratigraphy in the vicinity of the mine as a "zone of facies change from shallow-water stromatolitic dolostones to a more terriginous (*sic*) sequence of dolostones and carbonaceous siltstones and sandstones."

Amade (1986) and Lemcke (1986) drew heavily on Carr's (1981) unpublished work, but favoured the exhalative and rift-hosted models and reiterated the earlier idea that the host sediments to the Lady Loretta ore body were deposited in an anoxic sub-basin confined to a graben (although they identified a different graben to that defined by Dunnet (1976) - see Dunster and McConachie, in press*). They also advocated syn-sedimentary movement on the Carlton Fault Zone as the source of coarser sediments and as providing the conduit for mineralising fluids along the fault plane.

Neudert (1987) briefly studied the sedimentology of the mine stratigraphy and revived the idea that the hanging wall sediments were a series of small turbidite deposits in which he could recognise D, E and sometimes C units of the Bouma sequence.

In contrast to the lacustrine setting favoured for some other SSHBM host rocks, the theoretical study by Eugster (1987) regarded the Lady Loretta mineralisation and barite as forming by exhalation into a basin shortly after marine transgression.

In unpublished works, Harris (1984, 1993) used sedimentological and lithostratigraphic interpretations to suggest that the Lady Loretta and Esperanza Formations were coeval in the vicinity of the mine. He interpreted the ore host sediments as having been deposited in a shallow marine environment with restricted circulation in a graben setting.

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* *References marked with an asterisk are included in full in Appendix A-14.*

The summary of the features and setting of the Lady Loretta ore body by Hancock and Purvis (1990) again invoked a deep water anoxic sub-basin in a graben setting.

1.5.3 Concurrent Studies

This work was concurrent with two major studies. The AMIRA/ARC study of the northern Australian Proterozoic SSHBM ore bodies, conducted by researchers at CODES, has established a comprehensive database for the Lady Loretta ore body and proposed a new genetic model. A regional basins study of the Proterozoic of northern Australia (NABRE) was initiated by AGSO in 1995 and is currently in progress.

The present study was also contemporaneous with a study of the ore textures by Aheimer (1994) and a GIS investigation, based on gravity, magnetics and radiometrics, that was calibrated on the Lady Loretta ore body (Duffet, in prep.).

1.5.4 Sedimentological Studies of Other Northern Australian SSHBM Ore Bodies

This study should be compared with other sedimentological studies of the north Australian SSHBM host-rocks. The interpreted sedimentary settings of these ore bodies have never been well constrained and have been the subject of debate for decades. For example, there have been widely disparate interpretations for the Mount Isa host sediments, ranging from deep marine (Croxford and Jephcott, 1972; Russell *et al.*, 1981) to sabkha-intertidal (McClay and Carlisle, 1978). The most comprehensive sedimentological study of the Mount Isa host rocks was that of Neudert (1983) who concluded that they were deposited in a saline lake. Chapman (pers. comm., 1996) and Painter (pers. comm., 1996) supported this idea. The former correlated varve-like sediments over distances of kilometres and invoked deep water evaporites.

There are similarly divergent models for the depositional setting of the Barney Creek Formation that hosts the McArthur River (HYC) ore body (*cf.* Muir, 1983; Logan and Williams, 1984; and Bull, 1994; Bull and Rogers, 1996).

Some authors proposed similar depositional settings for the Lady Loretta, Mount Isa and McArthur River ore sediments, while others stressed the differences. Aspects of this argument are explored in Chapter 16.

1.6 TECHNIQUES AND METHODS OF STUDY

The field-based methodology used in the present study concentrated on the documentation of key sedimentary structures and the identification of potential bounding surfaces in measured sections of outcrop and in core. A total of over 80 km true stratigraphic thickness (tst) was documented from 29 locations and several cored drillholes (Table 1-2). These data were integrated with airphoto interpretations, local detailed mapping, palaeocurrent measurements, gamma ray logs, quantitative stratigraphic studies, thin section descriptions (including cathodoluminescence), isotope studies, geochemical analyses and diagenetic studies. Environments of deposition were interpreted and a first-pass sequence stratigraphic interpretation completed. Details of this methodology are given in respective Appendices.

Location Name	Map Code	AMG Co-ord.		True Thick. (m)	Graphic Log	Gamma Log	Geo-chem.	Ripple Analysis	Palaeocurrent Analysis	Quant. Strat.	Struct.	Salient Features
		Easting	Northing									
Bloodwood Bore	BLB	270000	7915300	1450	1:200	-	-	✓	-	-	f,s	2 short sections mid Pml, Pms contact previously mismapped
Brenda Creek Composite	BCC	269500	7896000	>2000	-	-	-	✓	✓	-	f	palaeocurrent analysis, quartzite in Pmz, Pml/Pms transition
Carrier	CAR	293500	7890000	1820	-	-	✓	-	-	-	f	outcrop equivalent to CRD1-5
Cartridge Creek Composite	CCC	292500	7903500	>2100	1:2500	-	-	✓	✓	-	f,s	complex folding, lower Pml, basal breccia
Cattle Creek	CAT	297500	7777000	1500	-	-	-	-	-	-	f,s	nose of syncline, mainly chert and silcrete, some ferruginous Pml
Greater Loretta Syncline	GLS	295000	7808500	1150-2500	1:2000	-	-	-	✓	-	f,s	outcrop comparable to mine sections
Gundaria Bore	GUB	304500	7764700	-	-	-	-	✓	✓	✓	f	silcrete, tidalites, palaeocurrent analysis
Inca Creek	INC	268667	7778630	1260	-	-	-	-	✓	-	f	silcrete, palaeocurrent analysis
Johnson Creek	JOC	286292	7774525	1200	-	-	✓	-	✓	-	f	Pml mostly recessive or silcrete
Kamarga Dome 1	KD1	271700	7922400	1520	1:200	-	-	✓	✓	✓	f	5 linked sections upper Pml, upper & lower Pml contacts mismapped
Kamarga Dome 2	KD2	270000	7925300	1415	1:200	-	-	✓	✓	-	f	Pml/Pms transition
Kamarga Dome 3	KD3	270000	7928300	1480	-	-	-	✓	✓	-	f	quartzite in Pmz, patchy outcrop of Pml
Kamarga Dome 4	KD4	271000	7931500	1370	1:200	-	✓	✓	✓	-	f	3 sections in Pml, giant ooids in 2 sections, 1 section in Pmz
Kamarga Dome 5	KD5	271400	7935300	1340	1:200	-	-	✓	✓	-	f	4 sections in Pml, 1 in Pmz
Kamarga Dome 6	KD6	274000	7939000	1440	1:200	-	-	✓	✓	-	f	section mid Pml
Lady Loretta Mine	LLD	297700	7812800	1280-1440	-	-	✓	✓	✓	-	f,s	palinspastic reconstruction
Lily Lagoon Composite	LLG	283200	7893200	2200	-	-	-	✓	✓	-	f	microbial facies and plate breccias in Pml, basal breccia
Line 3 Costean (LLD)	L3C	297209	7811943	-	-	✓	-	-	-	-	f	gamma log of costean
Mellish Park	MEP	310500	7894000	>1500	1:2500	-	-	-	✓	-	f,s	lower Pml, pyritic and microbial facies
Ogilive Range	OGR	265000	7749000	2400	-	-	-	-	✓	-	f	southern-most outcrops of Pml, poor exposure
Phosphate Plant (Pmz)	PHP	302000	7814000	-	-	-	-	-	-	-	f	basal breccia, Pmz/Pml contact
Ploughed Mountain	PMA	257500	7946500	-	-	-	-	-	✓	-	f	northern-most outcrops of Pml, palaeocurrent analysis
Police Creek	POC	294000	7874000	>1050	-	-	-	-	-	-	f,s	mismapping of Pml, basal breccia
Redie Creek Composite	REC	315000	7807000	>1750	-	-	-	✓	✓	-	f,s	basal breccia, Pmz/Pml contact
Russell Creek	RUC	288000	7823000	>1500	1:200	-	-	✓	✓	✓	f,s	upper and lower Pml contacts, 2 partial sections, Pmz not on pub. map
Seymour River	SER	287600	7860600	-	-	-	-	-	✓	-	f	palaeocurrent analysis
Thornton River	THR	291000	7850000	1860	1:2500	-	-	-	✓	-	f	complete type section
Trent Composite	TRE	286500	7809000	>1050	1:2500	-	-	✓	✓	-	f,s	red bed facies, basal breccia
Wangunda Bore	WAN	274800	7911800	1320	1:100	✓	-	✓	✓	-	f	detailed section mid Pml
Cored Drillhole												
Amoco 83-5		269800	7898900		1:100	✓	✓	-	-	✓	f	cyclic sedimentation, detailed log available on request
0740P148		296012	7811844	>239.9	1:200	✓	✓	-	-	-	f,s	Cyclic Unit, Ore Sequence Eq., Pyritic Unit, Big Syncline
2240P142		297272	7812678	>262.4	1:200	✓	✓	-	-	-	f,s	Cyclic Unit, Ore Sequence, Pyritic Unit, Small Syncline
2300P129		297292	7812745	>480	-	-	✓	-	-	✓	f,s	Cyclic Unit - 180 m analysed in detail
2315P91		297297	7812770	>356	-	-	✓	-	-	✓	f,s	Cyclic Unit - 10 m analysed in detail
2420ED62		297300	7812600	>386	-	-	-	-	-	-	f,s	microbial facies in Ore Sequence
LA64		299170	7815270	>316.9	1:200	✓	-	-	-	-	f	Cyclic Unit, Pyritic Unit
LA65		299000	7816000	>150.2	-	-	-	-	-	-	f	incomplete intersection, faulted lower contact
CM35		298750	7827000	>203.5	1:100	✓	-	-	-	-	s	lower Pml and Pmz/Pml contact
DDHJ1		308513	7758862	-	-	-	✓	-	-	-	f	geochem. of carbonaceous pyritic shales and carbonates
CRD1-5		293500	7890000	~2000	1:2500	✓	✓	-	-	-	f	geochem. of carbonaceous pyritic shales and carbonates

Table 1-2: Locations of field sections and key drillhole intersections of the Lady Loretta Formation examined during this study. In the structure column, the letter f indicates faults and s indicates folds.

Chapter 2 - Temporal Setting

2. TEMPORAL SETTING

2.1 THE SIGNIFICANCE OF A PROTEROZOIC SETTING

A Proterozoic setting has several unique aspects that must be borne in mind when applying the principles of uniformitarianism to the interpretation of such ancient sequences. The Earth-Moon-Sun system was probably not as we know today and this has implications for tidal deposition. Australia's Palaeoproterozoic tectonic evolution is poorly understood and there is still debate in the literature about the relative roles of crustal growth and plate tectonics during the Proterozoic. This has implications for the processes of sedimentary basin formation and evolution, especially in terms of the development of carbonate platforms, ramps and epeiric seas. The compositions of the Proterozoic atmosphere and oceans are far from certain and there are important differences between the Proterozoic and the present in terms of the abundance of dolomite and shallow marine evaporites, and with respect to the influences of living organisms on sedimentary processes.

2.2 GLOBAL DYNAMICS AND THE LAWS OF PHYSICS

Numerous authors (*e.g.* Carey, 1976; Klein, 1977; Salop, 1987; Sonett *et al.*, 1988, 1996; Vanyo and Awramik, 1985; Williams, 1991, 1993) have speculated about the dynamics of the Earth-Moon-Sun system during the Proterozoic and opinions remain divided as to the implications for sedimentology.

Studies of the angles of crossbed foresets led Mann and Kanagy (1990) to suggest that the angle of repose has decreased over time and that the force of gravity or interparticulate forces were lower during the Proterozoic. This idea has been championed by Earth-expansionists (*e.g.* Davidson, PESA Special Lecture 1996). However, the foreset dips measured from the Lady Loretta Formation do not support Mann and Kanagy's (1990) claims.

Klein (1977) refuted the propositions of Merifield and Lamar (1968) and Olson (1972) that because the moon was closer to the Earth during the Proterozoic, tidal intensity would have been higher and the preservation potential of tidal deposits would have been greater. Presumably, the periodicity of such deposits would also reflect a lunar cycle of different duration and Neoproterozoic examples documented by Williams (1989, 1991) and Sonett *et al.* (1996) support this idea. The calculations of Sonett *et al.* (1996) regarding the number of solar days per year indicate a different Earth-Moon separation and suggest that the solar year has become progressively shorter since the Proterozoic (from >400 days to *ca.* 365 days). However, the lunar period at 900 Ma (25 solar days) may have actually been less than at 650 Ma (30.5 solar days) and, indeed, even less than present. Vanyo and Awramik (1985) used the sinuous growth of columnar microbialites to infer a minimum of 410 solar days in the year at 850 Ma, in agreement with the work based on periodicity in tidal deposits. Few authors have attempted to quantify the Earth-Moon-Sun cycles older than Neoproterozoic. However, Klein (1977) cited evidence of several examples of typical tidalites (including herringbone cross-stratification - see Section 5.3.1) as old as 3.2 Ga and was of the opinion that the general dynamics of tidal sedimentation have been unchanged since the Archaean.

The tidal deposits of the Palaeoproterozoic Lady Loretta Formation, discussed in Sections 5.4 and Appendix A-10.4, are twice as old as some of the Neoproterozoic examples cited above and will add to this debate.

2.3 ATMOSPHERE

Inferences about the composition of the Proterozoic atmosphere are largely based on the geochemistry of banded iron formations (BIFs), studies of Proterozoic palaeosols and the temporal distribution of red beds. All three can be taken to indicate an increase in the O_2/CO_2 ratio from 2.2 to 1.8 Ga. The O_2 content was probably within a factor of two or three of its present level as early as 1.9 Ga and may have been similar to today by the Palaeoproterozoic (Klein, 1992). However, there is the possibility of a greenhouse effect during much of the Proterozoic because of elevated CO_2 levels (see discussion in Kasting, 1992). The CO_2 content of the atmosphere is a major control on the carbonate chemistry of the hydrosphere, as discussed below.

2.4 HYDROSPHERE

The water chemistry and relative sealevel must be able to explain several unusual aspects of the Proterozoic sedimentary record:

- prevalence of ?primary dolomite and shallow marine evaporites
- presence of Sr-enriched aragonite as the dominant primary carbonate at various times
- preservation of large amounts of organic matter
- widespread early silica diagenesis in the absence of a biological silica source.

It was suggested as early as 1907 that the ubiquitous Proterozoic dolomites were primary and resulted from a different seawater chemistry (Purser *et al.*, 1994). However, many of the better understood fabric-retentive Proterozoic dolomites are now recognised as early replacement although a suitable mechanism and water chemistry for this process has yet to be identified (Grotzinger, 1989).

At various times during the Palaeoproterozoic, seawater may have had a higher degree of saturation with respect to calcite and aragonite compared to the present. The rate of carbonate production also appears to have been greater than today, with the carbonate factory extending even into the realm of tidal flats (Adams and Grotzinger, 1996). Grotzinger (1989, 1993) suggested this to explain the prevalence of intertidal tufas (abiotic mesoscopic aragonite) before about 1.7 Ga and their absence thereafter. A similar interpretation has been made for giant Neoproterozoic "ooids" documented by Swett and Knoll (1989) and others (see Chapter 6). Sandberg (1985), amongst others, related the widespread occurrence of non-skeletal aragonite to periods of elevated atmospheric CO_2. The contrast between laterally continuous and mosaic peritidal carbonates as discussed by Adams and Grotzinger (1996) also reflects a different hydraulic and/or chemical hydrosphere and, ultimately, may be related to atmospheric CO_2.

Kempe and Degens (1985) proposed a Proterozoic bicarbonate "soda ocean" analogous to Lake Van in Turkey (Kempe *et al.*, 1991). Evaporites produced from such a system would include bicarbonates rather than sulphates. However, several Palaeoproterozoic marine formations (including the Lady Loretta Formation) contain the normal evaporitic sequence of carbonate → gypsum ± anhydrite → halite. This led Holland (1992) to conclude that the available data indicate a chloride and sulphate chemistry and salinity not greatly different from modern seawater, although there are no modern (Pleistocene to present) analogues for the extensive shallow marine evaporites in the older sedimentary record. This is best explained by the relatively recent, rapid fluctuations in sealevel which has prevented the preservation of such deposits (Warren, 1989), rather than a different seawater chemistry in the past.

The Palaeoproterozoic ocean may have been stratified leading to a lower O_2 concentration at depth. This would have contributed to a higher degree of preservation of organic carbon than today (Holland, 1992). Logan *et al.* (1995) suggested a feed-back mechanism whereby organic matter was extensively reworked as it sank slowly through the water column, and that the production of sulphide by sulphate-reducing bacteria would have inhibited O_2 transport in the deep ocean.

It is very difficult to predict what impact a Palaeoproterozoic greenhouse effect would have had on seawater chemistry. Biological processes currently undertaken by aquatic carbonate-secreting organisms and photosynthesis, today the major biological process in the ocean, would have been negligible. The interplay between increased atmospheric PCO_2 and the decreased solubility of CO_2 (due to higher surface temperatures) are the subject of current debate relating to the present green-house threat. Such affects may have profoundly changed the carbonate composition of Palaeoproterozoic seawater and may have had implications for the stability of iron minerals (Holland; 1973,1992; Sumner, 1995). Experiments have shown that varying the PCO_2 will also alter the ability of surface-temperature fluids to dissolve carbonates and precipitate silica (Hesse, 1989). This may explain the widespread silicification of Proterozoic carbonates in the absence of a biological silica source.

The isotopic composition and variations of pre-Neoproterozoic seawater are poorly understood. Secular variations in $\delta^{18}O$, $\delta^{13}C$ and $\delta^{34}S$ are based on limited data and there is a dearth of reliable $^{87}Sr/^{86}Sr$ data before the Neoproterozoic. Well-documented isotopic studies undertaken in the neighbouring McArthur Basin include formations probably contemporaneous with the Lady Loretta Formation (Veizer *et al.*, 1992). Some authors have accepted these as shallow marine and incorporated the isotopic data into global compilations (*e.g.* Veizer and Compston, 1976; Veizer *et al.*, 1992), while others (*e.g.* Eugster, 1987) regarded them as lacustrine and not indicative of seawater chemistry.

2.5 CLIMATE

Climate is undoubtedly one of the major controls on global sedimentology. There are few reliable indicators of palaeoclimate during much of the Proterozoic. There is no evidence of continental or marine glaciation during the late Palaeoproterozoic or Mesoproterozoic and deposition of the Lady Loretta Formation occurred between the severe global glacials of 2.4 Ga and 0.9 to 0.6 Ga. Ocean surface temperatures during this period may have been elevated by a positive feedback due to abnormally high atmospheric CO_2 associated with a greenhouse effect (Kastings, 1992). Work on O^{18}/O^{16} isotopes from cherts also lead some workers to speculate that interglacial ocean temperatures may have been higher than present (Savin, 1984).

During the absence of major continental ice sheets, sealevel oscillations are usually caused by small-scale obliquity and precession Milanokovitch rhythms. This favoured the deposition of cyclic peritidal platform carbonates during the early Palaeozoic and the Mesozoic (Wright, 1992b). Presumably, the sedimentary record of the ice-free Palaeoproterozoic should also contain widespread cyclic peritidal carbonates and examples have been documented by Grotzinger (1986a,b; 1989). Although there are such cycles in the Lady Loretta Formation (described herein); they are not as regionally extensive as those described from elsewhere.

Other workers (*e.g.* Pratt *et al.*, 1992) noted that modern narrow shelves do not normally contain broad muddy tidal flats. However, they are characteristic of the ice-free periods of Earth's history, including the Palaeoproterozoic.

Australia was moving towards the palaeo-equator from 1.6 Ga to 1.65 Ga. At the time of deposition of the Lady Loretta Formation, northern Australia was at approximately the same latitude as it is today (Loutit *et al.*, 1994; Idnurm *et al.*, 1995) and, even without the influence of a possible greenhouse effect, a similar warm temperate to subtropical climate might be expected. It is probably also significant that, at such latitudes, the region would be within the zone of present high storm intensity.

2.6 LIFE

The diversification of life during the Proterozoic is summarised by Schopf (1992).

Eukaryotes, in the form of single celled algae, were present by the late Palaeoproterozoic but there are no known examples of multicellular algae, protozoans or invertebrate metazoans. The Lady Loretta Formation was deposited during the ascendancy of the various cyano/bacterial forms that produce microbialites (stromatolites). Modern microbialites are poor analogues for the Proterozoic forms that filled the same niches as modern carbonate-secreting metazoa and calcifying algae. Some ancient microbial forms produced organic buildups comparable in size and character to Phanerozoic barrier, patch and pinnacle reefs (Grotzinger, 1989). Although thrombolites are known from older rocks (Kah and Grotzinger, 1992), they did not become abundant until the Early Cambrian and none were observed in the Lady Loretta Formation.

The Lady Loretta Formation was deposited in the absence of any burrowing, boring or grazing organisms. This contributed to the preservation of microbial fabrics and, in the absence of disruption of sediments by biological activity, enabled early cementation of shallow water carbonates. These microbial and early cemented crusts are the dominant clasts in the relatively abundant Proterozoic plate breccias (see Section 7.4). Modern shallow water shelfal and intertidal laminites are disrupted by extensive burrowing, whereas Proterozoic examples would have been preserved. Similarly, the bed forms of shallow marine storm deposits that are frequently not preserved in the modern environment because of the high rate of bioturbation might be more common in the Palaeoproterozoic record. It has also been argued that modern sea grasses stabilise shallow subtidal sea floors and that, in their absence, proportionally more silt- and sand-sized particles might have been moved onto tidal flats (Pratt *et al.*, 1992).

The absence of land plants, although commonly overlooked, is actually of great importance to sedimentological regimes. Presumably, rates of erosion and redeposition would have been greater. As a result, there may have been a greater input of terrestrial clastics into otherwise carbonate-dominated environments. High rates of sedimentation may also have contributed to the preservation of organic matter. The absence of terrestrial biomass and the relative abundance of carbonate during the Proterozoic undoubtedly affects the isotopic fractionation of $\delta^{13}C$.

2.7 PROTEROZOIC PLATE TECTONICS

Evidence from elsewhere in the world suggests that some form of plate tectonics provided the driving force for Palaeoproterozoic tectonism. The Palaeoproterozoic is thought to have been typified by tectonics that formed all or part of a Wilson cycle, while the Mesoproterozoic was generally thought to be a time of widespread rifting (Lowe, 1992). McConachie (1993) interpreted the Wilson cycle for the Palaeo- and Mesoproterozoic rocks of northwestern Queensland as having evolved from a rift, through a passive margin to a foreland basin.

On a broader scale, the Proterozoic plate-tectonic history of Australia is very poorly understood. It is generally accepted that Australia was part of the supercontinent of Rodinia, but opinions vary as to the details and timing of supercontinent formation and break-up (compare Borg and DePaolo, 1994; Hoffman, 1994; Idnurm and Giddings, 1996; Li *et al.*, 1996; Myers *et al.*, 1994; Powell and Li, 1994). Several workers (*e.g.* Bell and Jefferson, 1987; Idnurm and Giddings, 1996; McConachie, 1993b) suggested a relatively long-lived juxtaposition of north Australia and western Canada (Laurentia). This has implications for the types of basins developed and may be significant in terms of the similarities between the sedimentary geology in the two areas.

Points of inflection in the apparent polar-wander path for the period 1700-1500 Ma have been related to regional tectonic events, broad scale alteration and mineralisation in the Proterozoic of northern Australia (Loutit *et al.*, 1994).

Chapter 3 - Basinal, Stratigraphic and Structural Setting

3. BASINAL, STRATIGRAPHIC AND STRUCTURAL SETTING

3.1 BASINAL SETTING

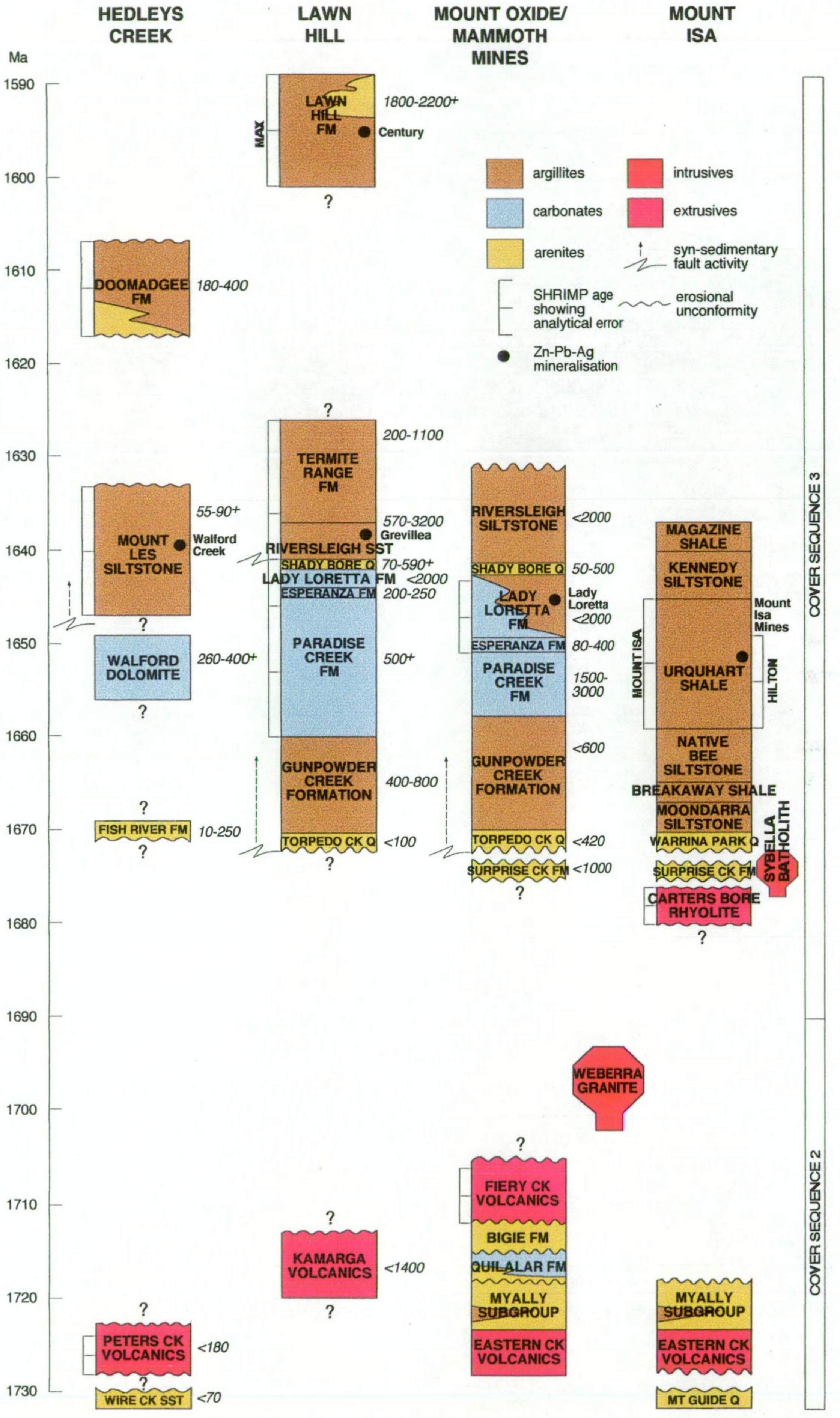
The basinal setting of the Palaeo- to Mesoproterozoic rocks of northern Queensland is the subject of several recent and current studies (O'Dea *et al.*, 1995; NABRE project). Most basin models, constrained only by surface outcrop and potential fields data and concentrated on the highly deformed areas around Mount Isa, have advocated failed rift or multiple rift-sag scenarios (*e.g.* Beardsmore *et al.*, 1988; Blake, 1987; Derrick, 1982; Gunn, 1983; O'Dea *et al.*, 1995). Etheridge *et al.* (1984) and Beeson *et al.* (1989) recognised a three component history; an early rift phase, a sag phase and a final clastic infill stage. Seismic data from the coeval, less-deformed northern-most flanks of the basin were also interpreted in terms of a three-stage evolution; from a rift, through a passive margin phase to a younger foreland wedge (McConachie *et al.*, 1993). In that model, the Lady Loretta Formation is part of a widespread shallow marine, carbonate-dominated platform sequence assigned to the passive margin phase by McConachie (1993b). A more-detailed study of the seismic data further subdivided the basin into a hierarchy of sequence stratigraphic units (Southgate *et al.*, 1996). Bradshaw *et al.* (1996) suggested that the Esperanza and Lady Loretta Formations might correlate to the sequence stratigraphic units Megasequence III - Supersequence III A of their interpretation, putting the Lady Loretta Formation into the foreland sequence as originally defined by McConachie (1993b). The basinal setting is discussed in more detail in McConachie *et al.* (1993) and McConachie and Dunster (1996, in press*).

3.2 REGIONAL STRATIGRAPHY

3.2.1 Introduction

The regional geology of the Proterozoic rocks of north Queensland was summarised by Blake (1987) and Blake *et al.* (1990), who divided the area into four major sequences. Ages obtained by Page and Sweet (in press) necessitate revision to Blake's (1987) classification (Figure 3-1). The oldest sequence, designated basement by Blake *et al.* (1990), was deformed and metamorphosed in the Barramundi Orogeny that ended at about 1870 Ma. Cover sequence 1 consists of the Leichhardt Volcanics. It is overlain by cover sequence 2 which contains a thick sequence of clastics and volcanics, now known to include the Fiery Creek Volcanics (1709 Ma), Peters Creek Volcanics (1726 Ma) and the Weberra Granite. The youngest, cover sequence 3, dates from about 1680 to 1590 Ma, and includes the Bigie Formation, Carters Bore Rhyolite (1678 Ma), Surprise Creek Formation and three laterally separate lithostratigraphic groups: the Fickling, McNamara and Mount Isa Groups (Figure 3-2). The Fickling Group is restricted to the north and separated from the central McNamara Group by the Elizabeth Creek Fault

Figure 3-1: The Proterozoic lithostratigraphy of the Hedley's Creek (near NT border) to Mount Isa area, northwest Queensland. This is a time-rock diagram showing the SHRIMP ages in Ma and their analytical uncertainties. Thicknesses are given beside the columns. Compiled from Blake et al. (1990), Loutit et al. (1994), McConachie (1993b), McConachie and Dunster (in press), Page and Sweet (in press).*


HEDLEYS CREEK
LAWN HILL
MOUNT OXIDE/ MAMMOTH MINES
MOUNT ISA
Ma
1590
1600
1610
1620
1630
1640
1650
1660
1670
1680
1690
1700
1710
1720
1730
LAWN HILL FM
1800-2200+
Century
MAX
argillites
carbonates
arenites
intrusives
extrusives
syn-sedimentary fault activity
SHRIMP age showing analytical error
erosional unconformity
Zn-Pb-Ag mineralisation
DOOMADGEE FM
180-400
TERMITE RANGE FM
200-1100
MOUNT LES SILTSTONE
55-90+
Walford Creek
570-3200
Grevillea
RIVERSLEIGH SST
SHADY BORE Q
70-590+
LADY LORETTA FM
<2000
ESPERANZA FM
200-250
PARADISE CREEK FM
500+
WALFORD DOLOMITE
260-400+
RIVERSLEIGH SILTSTONE
<2000
SHADY BORE Q
50-500
LADY LORETTA FM
Lady Loretta
<2000
ESPERANZA FM
80-400
PARADISE CREEK FM
1500-3000
MAGAZINE SHALE
KENNEDY SILTSTONE
Mount Isa Mines
MOUNT ISA
URQUHART SHALE
HILTON
NATIVE BEE SILTSTONE
BREAKAWAY SHALE
MOONDARRA SILTSTONE
WARRINA PARK Q
SYBELLA BATHOLITH
GUNPOWDER CREEK FORMATION
400-800
GUNPOWDER CREEK FORMATION
<600
FISH RIVER FM
10-250
TORPEDO CK Q
<100
TORPEDO CK Q
<420
SURPRISE CK FM
<1000
SURPRISE CK FM
CARTERS BORE RHYOLITE
WEBERRA GRANITE
FIERY CK VOLCANICS
BIGIE FM
QUILALAR FM
KAMARGA VOLCANICS
<1400
MYALLY SUBGROUP
MYALLY SUBGROUP
PETERS CK VOLCANICS
<180
EASTERN CK VOLCANICS
EASTERN CK VOLCANICS
WIRE CK SST
<70
MT GUIDE Q
COVER SEQUENCE 3
COVER SEQUENCE 2

Zone; whereas, the Mount Gordon Fault Zone and Mount Isa Fault separate the McNamara and Mount Isa Groups (see McConachie *et al.*, 1993 and McConachie and Dunster, in press* for details).

3.2.2 The McNamara Group

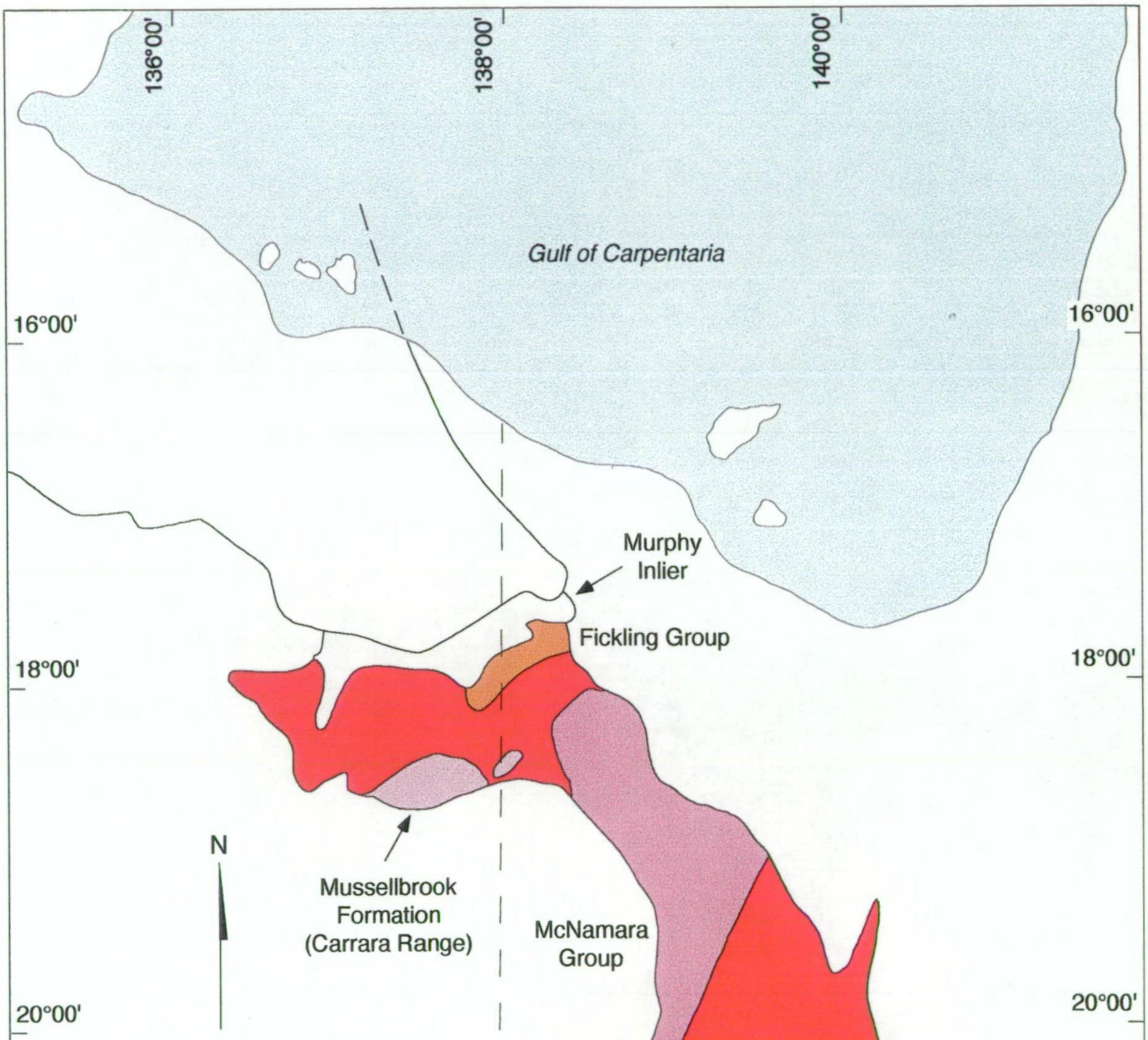
The McNamara Group was formally defined by Hutton *et al.* (1981) after Cavaney's (1975) original description of the unit. Company exploration during the early 1980's adopted the defined formation names but used slightly different lithostratigraphic definitions for the formations and adopted their own system of map codes. For example, assignation of all of the Plx_3 unit to the Esperanza Formation by Harris (1993) follows the previous company mapping and is not consistent with the usage of Hutton and Sweet (1981) as shown on some published Government maps. To add further confusion, the Government map codes and definitions of formations also vary from sheet to sheet. These revisions to the McNamara Group are summarised in Table 3-1. The McNamara Group has been informally subdivided into lower carbonate and upper clastic packages (*e.g.* Jones, 1986) and it has been suggested that the group may contain significant chronostratigraphic breaks (McConachie and Dunster, in press)*. Jackson *et al.* (1996) and Southgate *et al.* (1996) identified several major inter- and intraformational sequence boundaries that probably correspond to such breaks.

3.2.3 Esperanza Formation

The Esperanza Formation is a sequence of biostromal chert beds interbedded with, or grading laterally to, carbonaceous shales, siltstone, sandstone and minor dolostone. The formation is quite variable regionally, ranging from sandstone-dominated to spectacular biostromes that can be traced for kilometres along strike (Figure 3-3a). Columnar conical, large domed and branching columnar forms are most abundant, often forming distinct marker horizons. Elsewhere, the only microbialites present are small domes of columnar or digitate forms in otherwise clastic facies. Cauliflower cherts and gypsum pseudomorphs commonly occur within the cores of larger stromatolites in several localities. Harris (1993) and Hutton and Wilson (1985) documented other examples of evaporite pseudomorphs from the lower-most Esperanza Formation. The prevalence of highly carbonaceous shales within the Esperanza Formation is commonly overlooked, despite these having been drilled as a potential target for base metal mineralisation in several areas.

The Esperanza Formation typically varies in thickness between about 200 m and 400 m. A thinner section of 80 m was documented in the vicinity of the Mount Gordon Fault Zone (Hutton and Wilson, 1985).

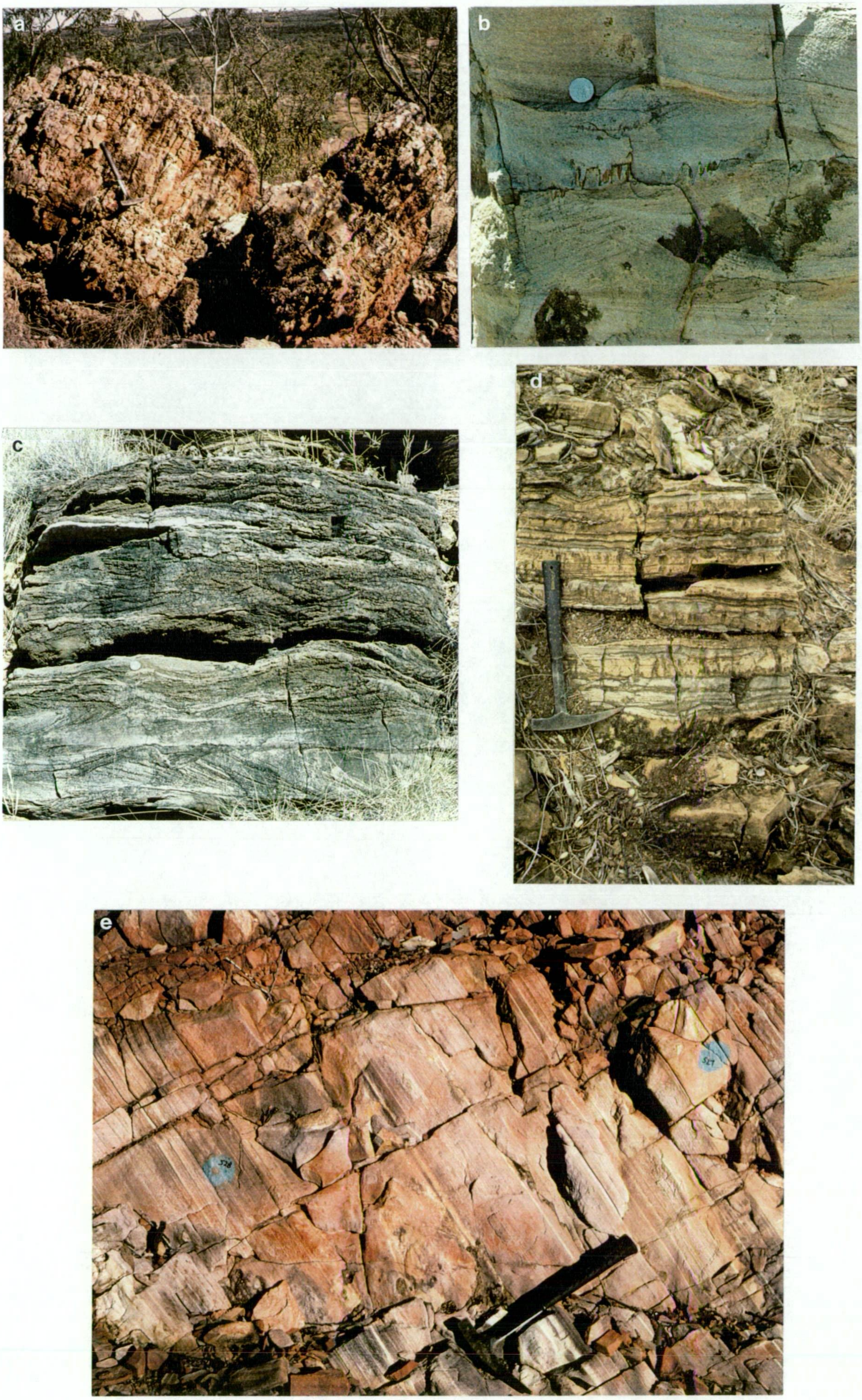
Figure 3-2: The geographical distribution of the Fickling, McNamara and Mount Isa Groups.


136°00'
138°00'
140°00'
Gulf of Carpentaria
16°00'
16°00'
Murphy
Inlier
Fickling Group
18°00'
18°00'
N
Mussellbrook
Formation
(Carrara Range)
McNamara
Group
20°00'
20°00'
200km
NT
QLD
WA
SA
NSW
VIC
TAS
Northern Territory
Queensland

<table>
<tr><th>De Keyser (1958)</th><th>Carter et al. (1961)</th><th>Cavaney (1975)</th><th>Sweet & Hutton (1981)</th><th>Company Mapping (1980 - 83)</th><th>Hutton et al. (1981)</th></tr>
<tr><td rowspan="3">Not Studied</td><td>Lawn Hill Formation</td><td>Lawn Hill Formation</td><td>Lawn Hill Formation</td><td>Lawn Hill Formation Plf</td><td>Lawn Hill Formation Pmh</td></tr>
<tr><td rowspan="3">Ploughed Mountain beds</td><td>Gregory Quartzite</td><td>Termite Range Formation</td><td>Termite Range Formation Plx$_3$</td><td>Termite Range Formation Pmt</td></tr>
<tr><td>Riversleigh Siltstone</td><td>Riversleigh Siltstone</td><td>Riversleigh Siltstone Plx$_2$</td><td>Riversleigh Siltstone Pmr</td></tr>
<tr><td rowspan="6">Paradise Creek Formation</td><td>Carrier Quartzite</td><td>Shady Bore Quartzite</td><td>Shady Bore Quartzite Plx$_1$</td><td>Shady Bore Quartzite Pms</td></tr>
<tr><td rowspan="5">Paradise Creek Formation</td><td rowspan="2">Lady Loretta Formation</td><td rowspan="2">Lady Loretta Formation</td><td>Lady Loretta Formation Plx$_5$</td><td>Lady Loretta Formation Pml</td></tr>
<tr><td>Breccia Plx$_{4a}$</td><td>Basal Breccia Pml$_b$</td></tr>
<tr><td>Esperanza Formation</td><td>Esperanza Formation</td><td>Esperanza Formation Plx$_4$</td><td>Esperanza Formation Pmz</td></tr>
<tr><td rowspan="2">Paradise Creek Formation</td><td>Paradise Creek Formation</td><td>Paradise Creek Formation Plx$_3$</td><td>Paradise Creek Formation Pmx</td></tr>
<tr><td>Chert Marker</td><td>Paradise Creek Formation Plx$_{1\&2}$</td><td>Mount Oxide Chert Member Pmo</td></tr>
<tr><td>Gunpowder Formation</td><td>Gunpowder Formation</td><td>Gunpowder Formation</td><td>Gunpowder Creek Formation</td><td>Gunpowder Creek Formation Plug$_{1-3}$</td><td>Gunpowder Creek Formation Pmw</td></tr>
<tr><td rowspan="2">Myally beds</td><td rowspan="2">Myally beds</td><td>Torpedo Creek Quartzite Member</td><td>Torpedo Creek Quartzite</td><td>Torpedo Creek Formation Plug$_{1a}$</td><td>Torpedo Creek Quartzite Pmp</td></tr>
<tr><td>Mammoth Formation</td><td>Surprise Creek Formation</td><td>Not Studied</td><td>Surprise Creek Formation</td></tr>
</table>

Table 3-1: Past and present lithostratigraphic nomenclature of the McNamara Group (shown stippled).

Figure 3-3: Typical lithologies from the Esperanza and Lady Loretta Formations and Shady Bore Quartzite. (a) Columnar microbialites near the top of the Esperanza Formation at Phosphate Plant. (b) Typical trough crossbedded orthoquartzite in the Shady Bore Quartzite at Russell Creek. Note the stylolite. (c) Crossbedded very coarse grained sandstone and granule conglomerate in the Lady Loretta Formation at Kamarga Dome. The sharp transition to the overlying carbonate is just visible at the top of the photo. (d) Typical thin bedded dolostone in the Lady Loretta Formation at Thornton River. (e) A costean exposure of the sequence underlying the Lady Loretta ore body and equivalent to the Lower Carbonate Unit in core. These highly weathered laminated siltstones and claystones are normally recessive and not seen in outcrop. Coin (3 cm d) and geology pick for scale.


a
b
c
d
e

The lithostratigraphic contact between the Esperanza and Lady Loretta Formations is a poorly defined "algaeformity" over the silicified microbialites assigned to the Esperanza Formation. The contact is inconsistent on published maps where the supposedly diagnostic microbialites are only sporadic along strike; or where the same, but unsilicifed, microbialites have been mapped as the Lady Loretta Formation. Using the so-called "basal breccia" of the Lady Loretta Formation to mark the contact has also caused errors (see below). During the current study, and that of southern Kamarga Dome by Cooper (1996), a highly distinctive and widespread bioherm was taken as the top of the Esperanza Formation (see Section 8.10).

3.2.4 Lady Loretta Formation - Regional Lithostratigraphy

The Lady Loretta Formation contains an extreme diversity of lithologies including granule conglomerate (Figure 3-3c), sandstone, siltstone, claystone, massive and thin-bedded carbonate mudstone (Figure 3-3d), ooid grainstone, microbial and intraclastic carbonate, chert and possible tuff.

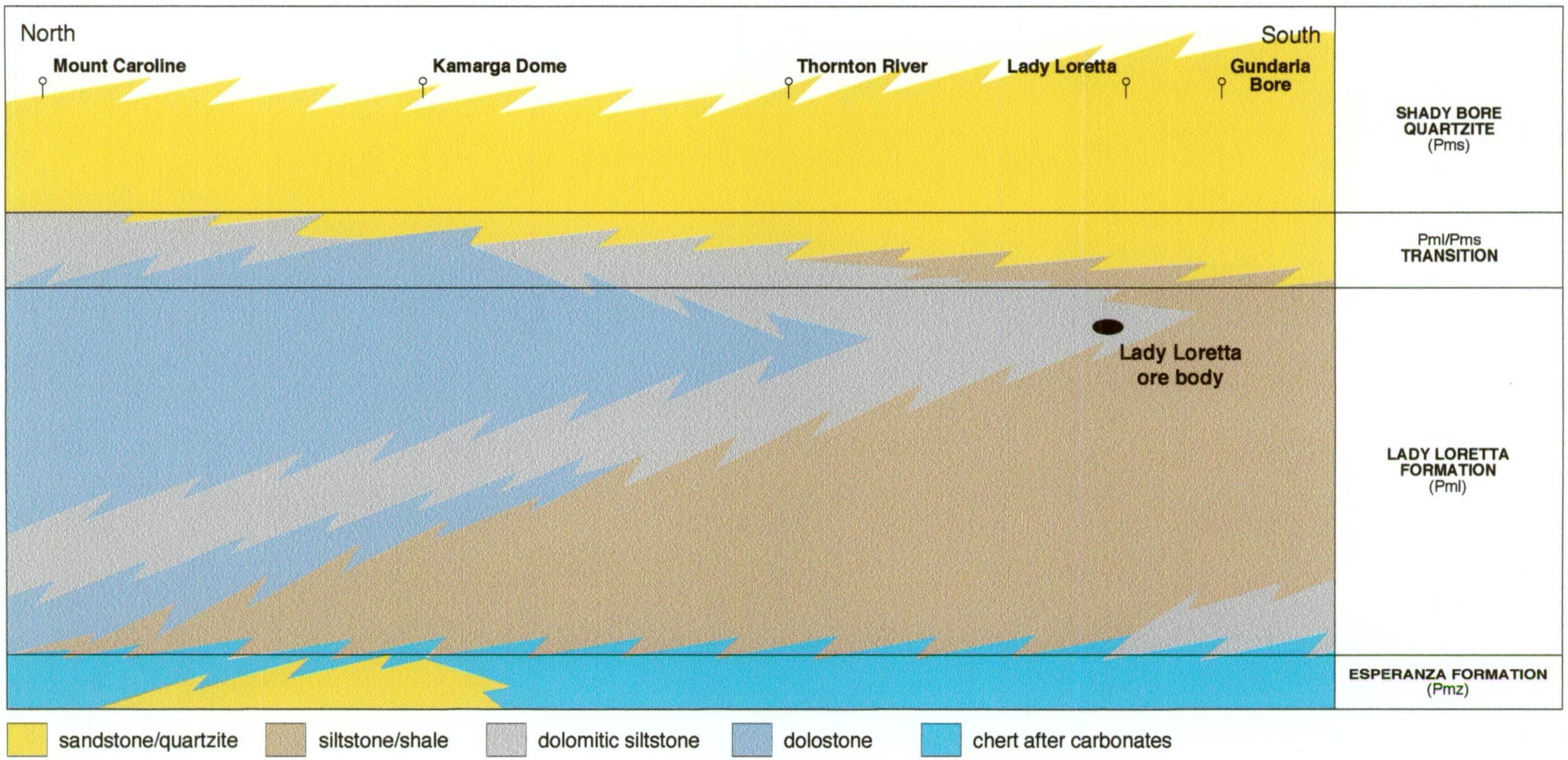
Broadly speaking, the Lady Loretta Formation is carbonate-dominated in the north on the Lawn Hill sheet and almost entirely argillaceous in the south on the Mount Oxide sheet (Figure 3-4). There are important local variations within this pattern. Significant thicknesses of shale do occur as far north as the flanks of Kamarga Dome. In the south, particularly around the Lady Loretta ore body, some of the formation previously mapped as clastic lithologies contains a significant carbonate component.

Highly pyritic and carbonaceous facies extend northeast from the ore body. Such facies are also known to occur as isolated pockets in various lithostratigraphic levels at Carrier, Mellish Park, (Beeson *et al.*, 1989), Johnson Creek (Taylor, 1973) and Police Creek (see Figure 3-5 for locations). Bedded barite is known only from the vicinity of the mine.

The Lady Loretta Formation is certainly not lithostratigraphically "layer-cake." Indeed, the intraformational lithological variability is such that it could be argued that the Lady Loretta Formation is not a valid lithostratigraphic entity. However, the gross changes are gradational, through both interbedding and transitional lithologies, and commonly occur over tens of kilometres laterally and tens or hundreds of metres vertically. Superimposed on this subtle regional variation, local changes occur along strike over hundreds of metres in mixed carbonate/siliciclastic facies. Previous attempts at lithostratigraphic subdivision of the formation, as shown on the published 1:100 000 maps, are commonly only local variations and have not been mapped consistently from one sheet to the next. Another sub-unit, an enigmatic basal breccia, mapped as Plm_b, has been demonstrated not to be a valid lithostratigraphic member (see Chapter 12).

Given these lithostratigraphic conundrums and the area involved (>1000 km^2), the present study has not attempted to re-map lithostratigraphic subdivisions of the Lady Loretta Formation but to recognise important formation-wide changes.

Figure 3-4: Schematic diagram showing the regional lithostratigraphic variation in the Lady Loretta Formation.



North
South
Mount Caroline
Kamarga Dome
Thornton River
Lady Loretta
Gundaria Bore
Lady Loretta ore body
SHADY BORE QUARTZITE (Pms)
Pml/Pms TRANSITION
LADY LORETTA FORMATION (Pml)
ESPERANZA FORMATION (Pmz)
sandstone/quartzite
siltstone/shale
dolomitic siltstone
dolostone
chert after carbonates

3.2.5 Lady Loretta Formation - Type Section and Reference Sections

The original type section for the formation (now hypostratotype) was defined in the vicinity of the Lady Loretta mine (Cavaney, 1975). Subsequent regional mapping by Government departments relocated the type section to the Thornton River (Hutton *et al.*, 1981) and defined additional reference sections at Wangunda Bore (Sweet and Hutton, 1980) and on the northern flanks of Kamarga Dome (Sweet and Hutton, 1982). No graphic logs or detailed descriptions were published. All of these formal sections have been re-described during the present study and graphic logs are included in Appendix A-15.

3.2.6 Lady Loretta Formation - Distribution and Nature of Outcrop

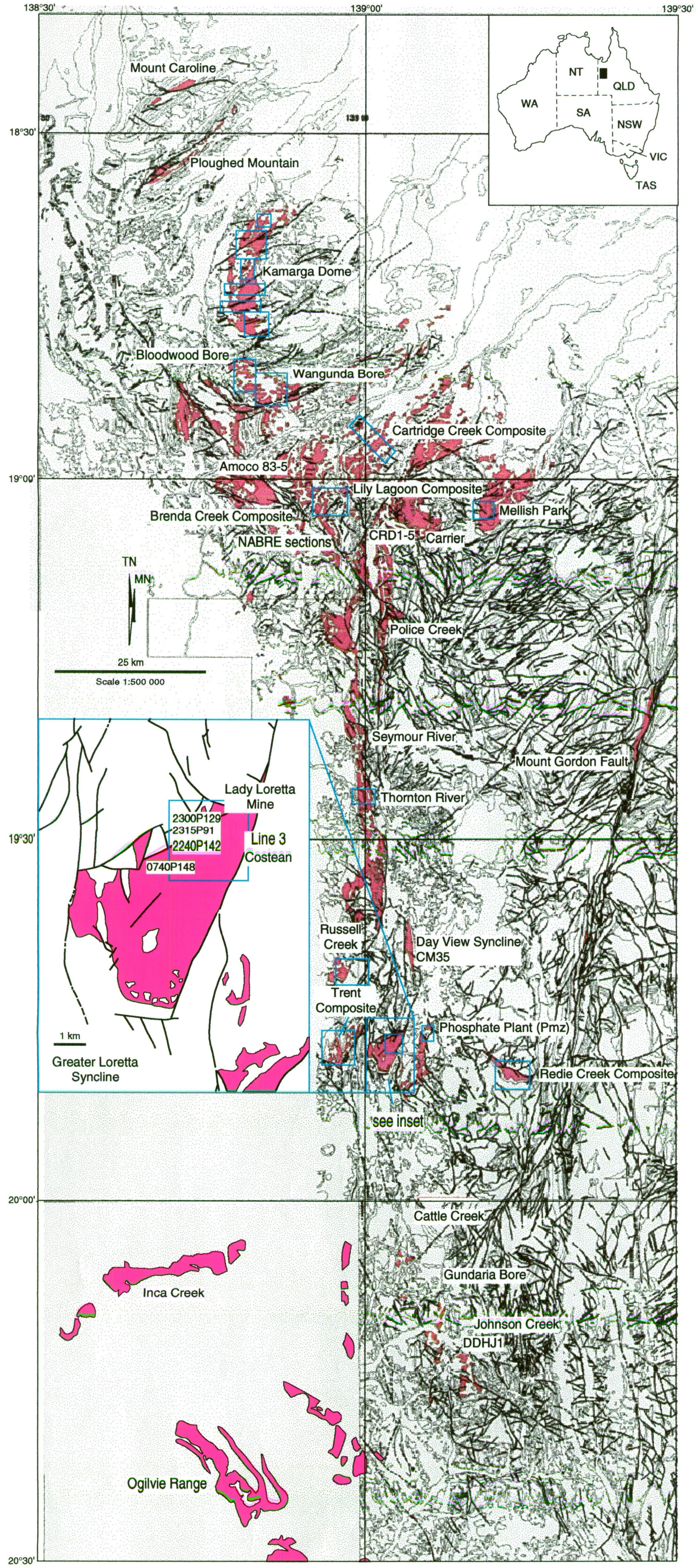
The Lady Loretta Formation can be recognised, as outcrop or subcrop, over an area of >3500 km^2 from Ogilvie Range in the south, 250 km north to Mount Caroline (Figures 1-1, 3-5). No depositional edge has been identified. Chronostratigraphic and/or litho-stratigraphic equivalents may exist in the Mount Isa Group to the southeast, in the Fickling Group (see McConachie and Dunster, in press*) and the Carrara Range (NT) to the northwest. The Lady Loretta Formation is well exposed in outcrop locally in the north, especially on the flanks of Kamarga Dome. Exposure is poor to almost non-existent in the south on the Mammoth Mines and Kennedy Gap 1:100 000 maps.

The extent of weathering has been understated in the geological literature but is better documented in geomorphological articles (*e.g.* Ollier; 1988, 1991a,b). In addition to the present, parts of the Lady Loretta Formation were exposed and weathered during the Cambrian, Jurassic-Cretaceous and Tertiary. This led to the superimposition of weathering surfaces. During the Cambrian, much of the southwestern Lady Loretta Formation was reduced to a series of palaeo-valleys between the more resistant outcrops of the silicified Esperanza Formation and Shady Bore Quartzite. These palaeo-valleys have been excised by modern erosion; but, in places, a thin veneer of fossiliferous Cambrian sedimentary rocks remain. Commonly, this Cambrian cover has been mismapped as Lady Loretta Formation on published maps.

Much of the outcrop is silicified and/or ferruginised. Silcrete caps have been previously mismapped as Shady Bore Quartzite on the Kennedy Gap 1:100 000 sheet. A problematic breccia caps the outcrop of the lower Lady Loretta Formation over much of its outcrop (see Chapter 12).

Elsewhere, drillholes show that weathering and leaching can extend to >100 m beneath the present surface and may extend to 300 m adjacent to faults (Cox and Curtis, 1977). Supergene minerals occur in excess of 100 m below the surface at the Lady Loretta mine. This saprolite depth is not unusual compared to other examples cited by Ollier (1988), particularly in areas subjected to weathering during the Mesozoic. However, in the vicinity of the ore body some of this apparent deep weathering may be related to alteration associated with mineralisation (Grant, pers. comm., 1996).

Figure 3-5 (fold-out): Outcrop of the Lady Loretta Formation as shown on published maps. The areas studied in detail are indicated.



138°30'
139°00'
139°30'
18°30'
19°00'
19°30'
20°00'
20°30'
NT
QLD
WA
SA
NSW
VIC
TAS
Mount Caroline
Ploughed Mountain
Kamarga Dome
Bloodwood Bore
Wangunda Bore
Cartridge Creek Composite
Amoco 83-5
Lily Lagoon Composite
Mellish Park
Brenda Creek Composite
NABRE sections
CRD1-5
Carrier
TN
MN
Police Creek
25 km
Scale 1:500 000
Seymour River
Mount Gordon Fault
Lady Loretta Mine
Thornton River
2300P129
2315P91
2240P142
Line 3 Costean
0740P148
Russell Creek
Day View Syncline
CM35
Trent Composite
Phosphate Plant (Pmz)
1 km
Greater Loretta Syncline
Redie Creek Composite
see inset
Cattle Creek
Gundaria Bore
Inca Creek
Johnson Creek
DDHJ1
Ogilvie Range

3.2.7 Lady Loretta Formation - Drillhole Data

The drillhole information for the Lady Loretta Formation consists of cores of incomplete sections and shallow RAB holes. Table 3-2 lists those cored drillholes studied in detail in the current study. Those prefixed by numbers are selected representative cores from the vicinity of the Lady Loretta ore body. The abbreviations used in these drillhole names are explained in Appendix A-4.

Drillhole	Easting	Northing	Cored Interval (m)	True Strat. Thickness (m)
Amoco 83-5	269800	7898900	6.0-582.2	<582.2
0740P148	296012	7811844	6.7-269.0	239.9
2240P142	297272	7812678	4.57- 331.62	262.4
2300P129	297292	7812745	*ca.* 212-696	<484
2315P91	297297	7812770	*ca.* 24-356	<332
LA64	299170	7815270	102.7-406.0	316.9
LA65	299000	7816000	96.0-249.0	150.2 (top at 42.3 m)
CM35	298750	7827000	114.0-349	203.5
CRD1-5	293500	7890000	various	composite

Table 3-2: Summary of key cored drillhole intersections used in the current study.

3.2.8 Lady Loretta Formation - Thickness

The formation is typically about 1300 m to 2000 m thick regionally (Figure 1-1, Table 1-2). However, thickness estimates in the vicinity of the Lady Loretta mine vary. Hutton *et al.* (1981) calculated less than 600 m near the outcrop of the mineralised sequence, whereas Hutton and Wilson (1985) stated that the formation was about 1800 m thick in the Greater Loretta Syncline. Binks (1975) estimated 1200 m and Russell *et al.* (1976) estimated a thickness of in excess of 1500 m; in agreement with Dunster and McConachie (in press)* who suggested a minimum of 1150 m and a maximum of 2500 m in the Greater Loretta Syncline. At the mine itself, the best estimate for a depositional thickness is probably between 1280 m and 1440 m, prior to the lower portion being faulted out beneath the ore body. In the present structural configuration, only about 600 m of stratigraphy is preserved in the axis of the syncline hosting the ore body.

3.2.9 Age of the Lady Loretta Formation

The age of the Lady Loretta Formation is constrained by dating of the stratigraphically-lower Paradise Creek Formation (1653±7 Ma - Page *et al.*, 1994) and the overlying Termite Range Formation (1636±10 Ma - Page, pers. comm., 1995), putting it in the late Statherian Period of the Palaeoproterozoic Era using the timescale of Plumb (1991).

During the current study, SHRIMP (sensitive high-resolution ion microprobe) dating of euhedral zircons from a highly altered tuffaceous bed a few tens of metres stratigraphically below the level of orebody gave a depositional age of 1647±4 Ma (Page, pers. comm., 1997). The Pb model age of the mineralisation is discussed in Chapter 13.

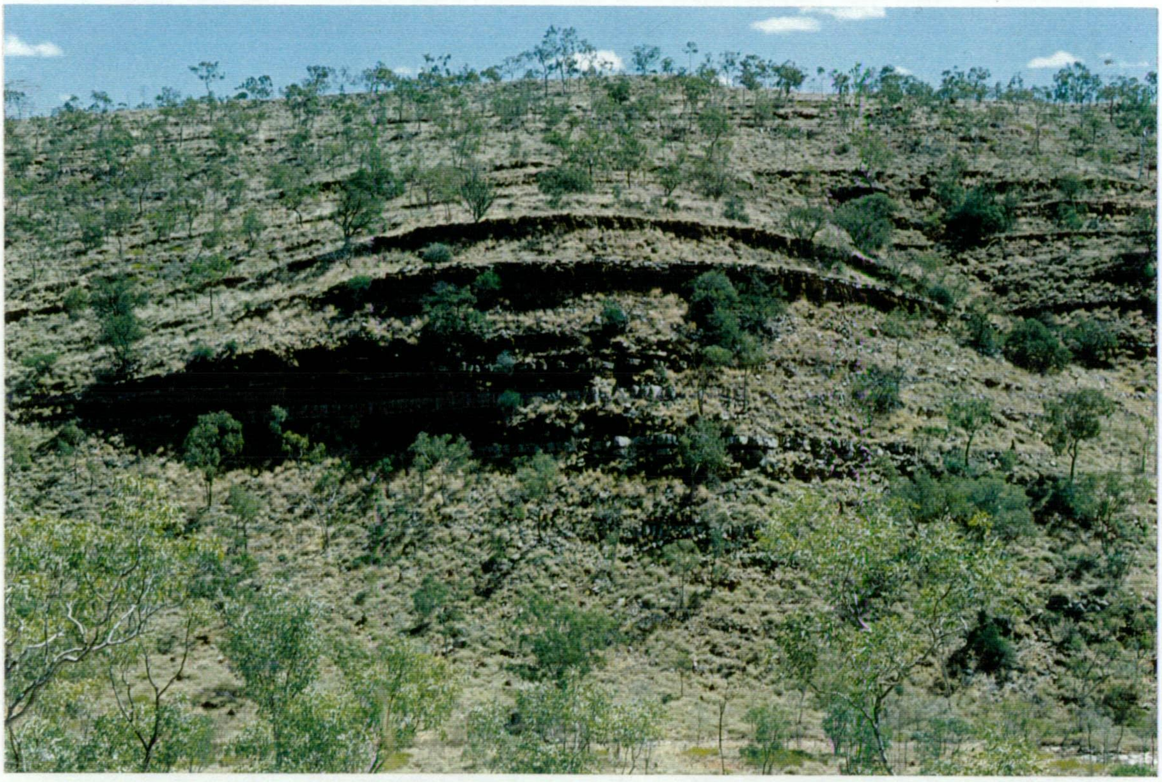
3.2.10 Shady Bore Quartzite

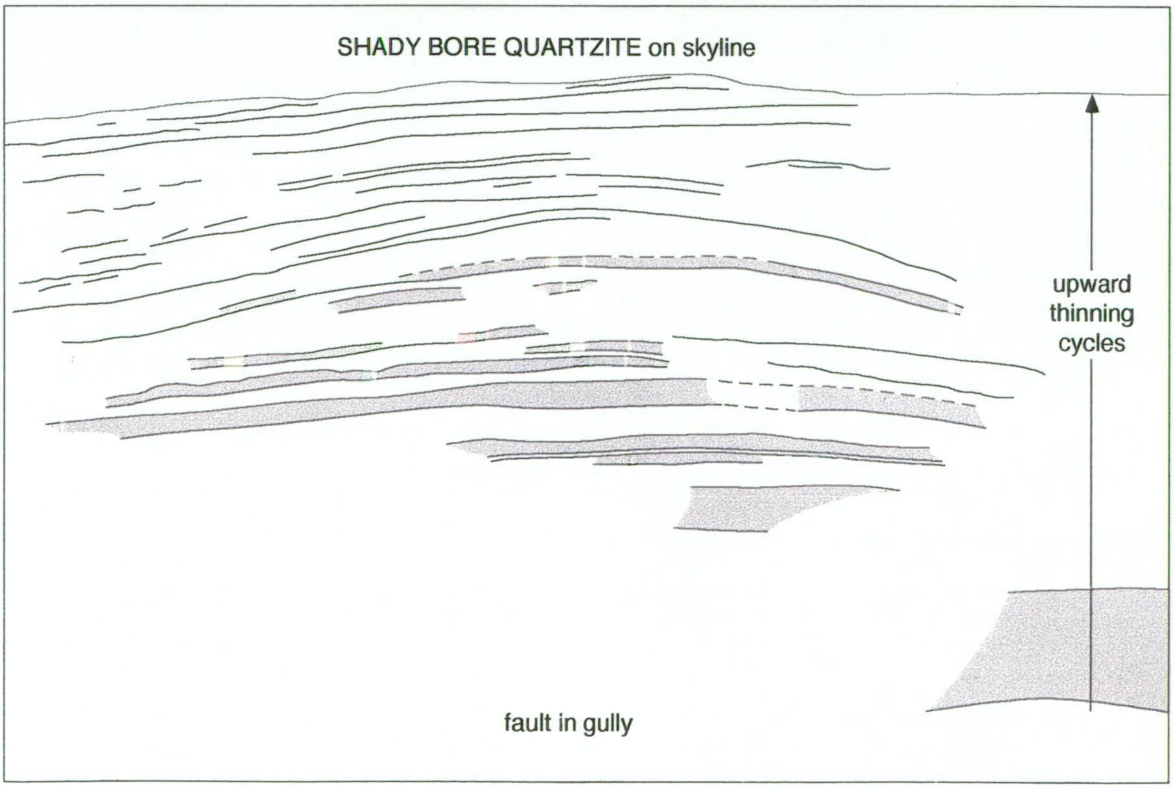
The Shady Bore Quartzite comprises white flaggy to massive medium grained orthoquartzite and feldspathic quartz sandstone with subordinate fine grained sandstone, siltstone and dolostone interbeds. The Shady Bore Quartzite overlies the Lady Loretta Formation and, generally, the contact has been regarded as transitional, through the interbedding of carbonates and siliciclastics, over tens of metres. Hutton *et al.* (1981) defined the contact at that point where massive orthoquartzite beds form 25 percent of the section. In practice, their published map does not always follow this, and instead uses the base of the first pronounced quartzite ridge visible on airphotos. The transitional zone has been mapped as Pml_t and included within the Lady Loretta Formation on the published Lawn Hill Region 1:100 000 sheet, but has been included in the Shady Bore Quartzite as shown on the Kennedy Gap 1:100 000 sheet. The transition zone has not been differentiated on the other published maps and has not been consistently assigned to one formation or the other.

Cavaney (1975), in his original definition of the formations, accepted that the sandy facies exposed in the core of the Big Syncline could be assigned to the Shady Bore Quartzite and attributed a thickness of about 60 to 100m to the quartzite in the vicinity of the Lady Loretta ore body. However, this has been mapped as Lady Loretta Formation on the published 1:100 000 scale maps. These outcrops could be assigned to the lower-most transition zone between the two formations.

Several workers (Dorrins *et al.*, 1983; Pringle and David, 1983; McConachie, 1993b; Keele, 1994; Daneel, pers. comm., 1995; Henry, pers. comm., 1995) speculated about an erosional or locally angular unconformable relationship between the Lady Loretta Formation and the Shady Bore Quartzite. Specific localities discussed by these workers were examined during the current study and were found to be either conformable (Figure 3-6) or faulted. Bradshaw *et al.* (1996b) subsequently described several unconformities within the Riversleigh Siltstone and Shady Bore Quartzite in the Police Creek to Brenda Creek area and, in agreement with Henry (pers. comm., 1996), confirmed the lithostratigraphically transitional nature of the Lady Loretta Formation to Shady Bore Quartzite contact in these areas. However, Krassay *et al.* (1997) recognised a major incision surface at Freemans Creek described "as the base of an incised valley overlain by 50 m of coarse-grained, conglomeratic, poorly-sorted, trough crossbedded, lithic arenites." These were interpreted as fluvial deposits and the erosional surface, termed Event E, was interpreted as an unconformity between the Lady Loretta Formation and Shady Bore Quartzite. This event subsequently became a key surface for sequence stratigraphic correlation (*e.g.* Bradshaw and Scott, 1997). In deference to the wishes of the lease-holders, the author was unable to visit this location. However, in view of the transitional nature of the lithostratigraphic contact between the Lady Loretta Formation

Figure 3-6: Transitional contact between Lady Loretta Formation and Shady Bore Quartzite.




SHADY BORE QUARTZITE on skyline
upward
thinning
cycles
fault in gully

and Shady Bore Quartzite elsewhere, the significance of this single location should not be overstated. It is possible that the sequence stratigraphic surface is strictly intra-Shady Bore Quartzite and has incised lower at this one location (see discussion in Section 10.3.3).

The Shady Bore Quartzite typically varies between 50 and 500 m thick but may be considerably thicker in the south (McConachie, pers. comm., 1995). Sweet and Hutton (1980) showed it thinning markedly to the east in the Police Creek to Thornton River area. Krassay *et al.* (1997) noted thinning to the north because of onlap. The lower portion of the formation contains numerous coarsening-up cycles and the upper section contains both fining- and coarsening-up cycles. Trough crossbeds are ubiquitous and other forms of compound crossbedding, including herringbone, occur sporadically. Wave, current and combined-flow ripples have all been recognised. Desiccation and synaeresis cracks (including all the morphologies described from the Lady Loretta Formation - Section 5.7.4) are locally common in the Shady Bore Quartzite. Casts and moulds of both halite and pyrite also occur. Distinctive horizons of mud clast breccias, in which the <1 cm d flake-like clasts have preferentially weathered out, form local marker horizons. The flakes are similar to the "microbial sand chips" of Pflüger and Greese (1996).

Sweet and Hutton (1980) noted that the northern-most outcrops of the Shady Bore Quartzite were characterised by arenaceous facies and lacked the argillaceous and carbonate lithologies evident in the south. Variably silicified carbonate interbeds are sporadically exposed from Mount Caroline in the north to Gundaria Bore in the south. These dolostones include microbial bioherms and biostromes and beds of ooid grainstone at Kamarga Dome.

The Shady Bore Quartzite is believed to have been deposited in marine, paralic and fluvial conditions. Using the interpretations of Bradshaw *et al.* (1996b) and Krassay *et al.* (1997), there appears to be a central fluvial package with transitional marine environments above and below.

3.3 LITHOSTRATIGRAPHY IN THE VICINITY OF THE LADY LORETTA ORE BODY

The oldest rocks exposed in the vicinity of the mine occur in a faulted anticline 4 km to the north of the mine. At this locality, the coarse clastics of the ?Bigie Formation occur adjacent to the Western Border Fault and are overlain, presumably unconformably, by distinctive salmon pink quartzites of the Surprise Creek Formation.

Approximately 30 m thickness of highly weathered basic volcanic rocks are exposed in the core of a large anticline 2.0 km northwest of the mine. These were assigned to the Fiery Creek Volcanics by Hutton and Wilson (1985). However, Russell (unpublished, cited in Hutton and Wilson, 1985) believed that they were more closely related to the Eastern Creek Volcanics based on the geochemistry. The volcanics were intersected beneath a fault in a cored drillhole and Carr (1981) described the mineralogy as chlorite and quartz with accessory dolomite, sericite, orthoclase and haematite.

Amygdules filled with quartz and coarse chlorite are locally common in both the outcrop and cored intersections. It is noteworthy that this is the only example of volcanics for tens of kilometres in any direction, although geophysical data can be interpreted to suggest that they are more extensive in the subsurface (Duffet, pers. comm., 1995). Attempts to date the volcanics have been unsuccessful.

The volcanics are overlain by a poorly sorted sandstone and conglomerate. These units were mapped as Surprise Creek Formation by Hutton and Wilson (1985). However, the lithostratigraphic affinity of these coarse clastics is open to question because the exposure is very poor and complicated by numerous faults. Elsewhere, the Surprise Creek Formation proper is overlain by the Torpedo Quartzite. The nature of this contact and thickness changes across it are described in Keele *et al.* (1996) and Bull (1996b) and can be interpreted as evidence of syn-sedimentary fault activity.

The remainder of the overlying lower McNamara Group consists of the Gunpowder Creek, Paradise Creek, Esperanza and Lady Loretta Formations.

The Gunpowder Creek Formation consists of micaceous and chloritic siltstones, shales, minor dolomitic siltstone, dolostone and fine grained sandstone (Carr, 1981). Some argillaceous horizons are highly carbonaceous and pyritic. The Gunpowder Creek Formation is up to 600 m thick and local thickness variations north of the Lady Loretta mine have been attributed to syn-sedimentary faulting (Keele *et al.*, 1996).

The contact between the Gunpowder and Paradise Creek Formations is marked regionally by a distinctive faintly laminated chert called the Mount Oxide Chert. There appears to be some minor mismapping of other chert horizons as Mount Oxide Chert, especially in the numerous small fault blocks north of the mine. South of the mine, the Mount Oxide Chert is well exposed and the overlying Paradise Creek Formation may be in excess of 3000 m thick (Carr, 1981). North of the mine, Keele *et al.* (1996) calculated a thickness of >1500 m. The Paradise Creek Formation consists of variably dolomitic laminated siltstones and claystones with local development of highly carbonaceous and pyritic shales and microbialite units.

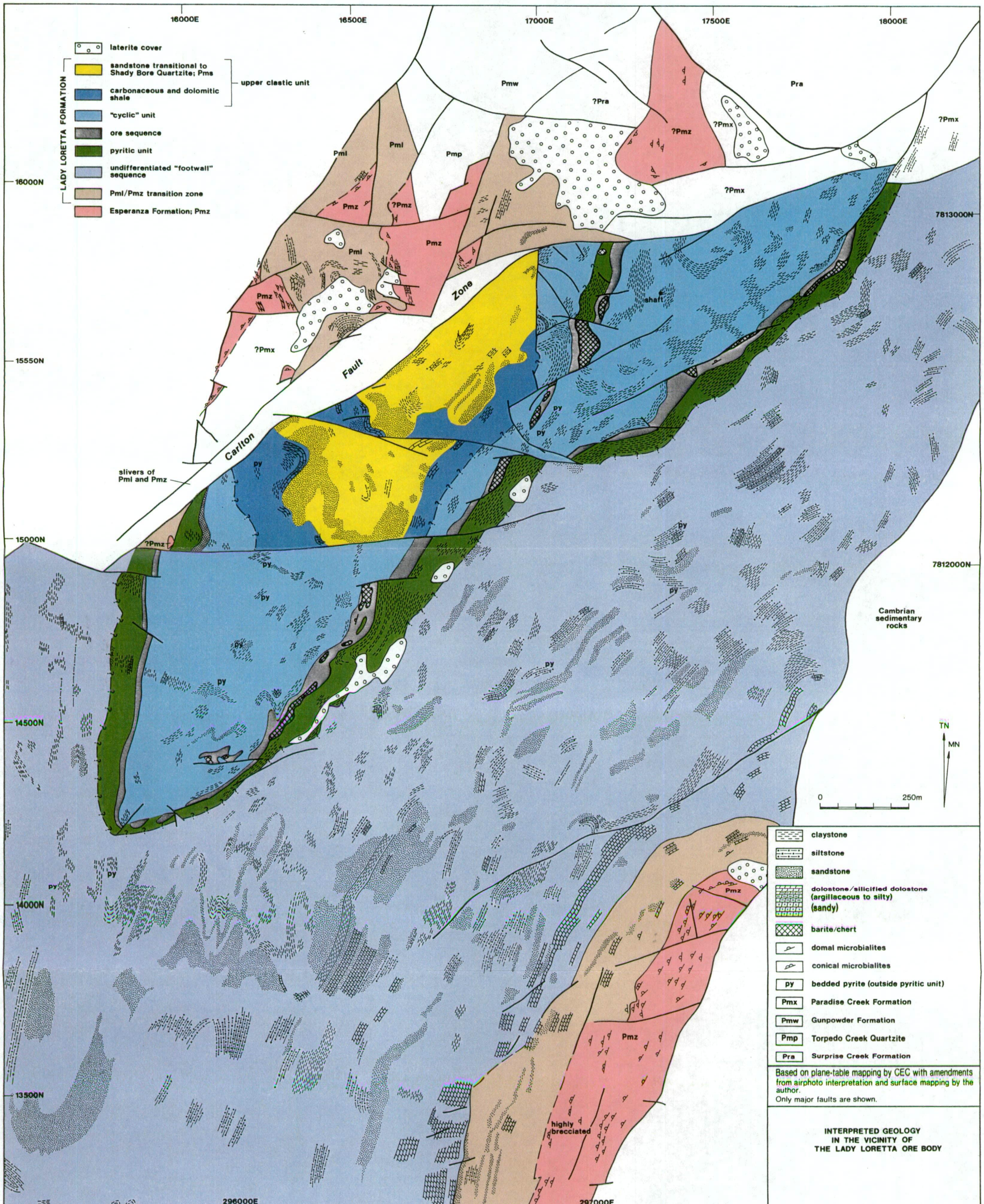
The overlying Esperanza Formation is generally poorly exposed in the vicinity of the mine and the 250 m thickness quoted by Hutton and Wilson (1985) is probably a minimum. The high-relief microbialites that define this unit elsewhere are less conspicuous in the outcrops in the Greater Loretta Syncline and the exposed chert horizons are typically prone microbial laminites. North of Carlton Fault Zone, the basal Esperanza Formation is exposed in several small fault blocks where it contains bioherms of digitate microbialites and microbial laminites. Further north, 12 km from the mine, Hutton and Wilson (1985) noted that only low-relief bioherms were present and interpreted this as reflecting shallower water. However, to the east of the mine there are well developed high-relief conical microbialites near the contact between the Esperanza and Lady Loretta Formations. The Esperanza Formation is conformably overlain by the Lady Loretta Formation except on the eastern limb of the Greater Loretta Syncline, where the contact is a fault. Esperanza Formation is exposed adjacent to Western Border Fault to the south of the mine but this is not mapped on the published 1:100 00 sheet. On a small scale, the lithostratigraphic contact between the formations is commonly gradational and has been mapped as a transition zone on the detailed interpreted geology in the vicinity of the mine (Figure 3-7). Near Western Border Fault, the transition zone contains interbedded dolostones with sporadic microbialites and sandstones. Some of the latter contain flaser and lenticular bedding. The basal few metres of the Lady Loretta Formation is marked by a laminated and thin bedded dolostone devoid of microbial fabric. The contact between the Esperanza and Lady Loretta Formations is also gradational north of the Carlton Fault Zone. Here the transition zone is similar to the western limb of the Greater Loretta Syncline and consists of highly ferruginous argillites.

The lithostratigraphy of the Lady Loretta Formation in the vicinity of the mine has been sub-divided as shown in Table 3-3. The current study simplified the previous nomenclature so it can be extended away from the mine. The lithostratigraphic correlation to the Tom Cat area, *ca.* 3 km northeast of the mine, is based on slightly different definitions of the units to those originally used by Donaldson (1985). The current assignation of the units is shown on the composite section for the Greater Loretta Syncline and logs for drillholes LA64, LA65, 0740P148 and 2240P142 (Appendix A-15). Note that this local stratigraphy is less than half of the total thickness of the Lady Loretta Formation exposed in the vicinity of the mine; the lower portion remains undifferentiated because of poor outcrop and lack of drillhole intersections.

The "Lower Carbonate Unit" is typically about 200 m thick and was studied in core from underground drilling at the mine and in several costean exposures (Figure 3-3e). This unit consists of thinly bedded to laminated, variably dolomitic siltstone, claystone and carbonaceous shale with subordinate dolostone and sandstone. Carr (1981) identified a "tuff" in this sequence and other tuffaceous sediments were recognised during the present study (see Section 11-6). The unit is characterised by monotonous planar lamination, although sporadic wave-ripple cross-lamination and small low-angle trough crossbeds are also locally common, particularly in the Big Syncline. Flaser bedding and synaeresis cracks were identified in outcrop. Carbonates are more prevalent in the Small Syncline and the unit is increasingly sideritic up-section. Pyrite, where present, generally occurs as sub-millimetre cubes but thin laminated pyrite beds also occur locally. Gypsum veins are most abundant in this unit. The lower boundary of the unit is defined by the occurrence of dolomite beds in the Small Syncline, but is more difficult to define elsewhere and has been placed at the base of a sandstone in outcrop in the Big Syncline to be consistent with the CEC mine map. Some of what was described as the Lower Dolomitic Unit by Carr (1981) and Hancock and Purvis (1990) is now recognised as having been faulted into place and may not be Lady Loretta Formation.

The Lower Carbonate Unit is overlain by the "Pyritic Unit". In the Big Syncline, the Pyritic Unit ranges between 25 m and 80 m thick and consists of interbedded silty shale, dolomitic siltstone, shaly fine grained sandstone, carbonaceous shale and ubiquitous

Figure 3-7 (fold-out): Interpreted geology in the vicinity of the Lady Loretta ore body.



16000E
16500E
17000E
17500E
18000E
laterite cover
LADY LORETTA FORMATION
sandstone transitional to Shady Bore Quartzite; Pms
carbonaceous and dolomitic shale
upper clastic unit
"cyclic" unit
ore sequence
pyritic unit
undifferentiated "footwall" sequence
Pml/Pmz transition zone
Esperanza Formation; Pmz
16000N
15550N
15000N
14500N
14000N
13500N
7813000N
7812000N
Pmw
Pra
?Pra
?Pmz
?Pmx
Pml
Pmp
Pmz
Carlton Fault Zone
shaft
py
slivers of Pml and Pmz
Cambrian sedimentary rocks
TN
MN
0
250m
claystone
siltstone
sandstone
dolostone/silicified dolostone (argillaceous to silty)
(sandy)
barite/chert
domal microbialites
conical microbialites
py bedded pyrite (outside pyritic unit)
Pmx Paradise Creek Formation
Pmw Gunpowder Formation
Pmp Torpedo Creek Quartzite
Pra Surprise Creek Formation
Based on plane-table mapping by CEC with amendments from airphoto interpretation and surface mapping by the author.
Only major faults are shown.
highly brecciated
296000E
297000E
INTERPRETED GEOLOGY IN THE VICINITY OF THE LADY LORETTA ORE BODY
Author: J. Dunster
Date: March '96

bedded pyrite. Minor barite and "tuff" occur locally. Similar lithologies, with the exception of barite and "tuff", were intersected in the Tom Cat area. Pyrite, carbonaceous shale and sideritic dolostone are more abundant in the Small Syncline and commonly account for approximately 70%, 15% and 5% of the total volume respectively. Bedded barite is present in the northwestern limb of the Small Syncline. Sideritic alteration is less pervasive than in the Lower Carbonate Unit, but does extend to both the Big Syncline and the Tom Cat area. The current study has followed the stratigraphy shown on the underground mine sections and assigned some of the section in the southern Small Syncline that was termed the "Lower Sideritic Unit" by Carr (1981) to the Pyritic Unit since pyrite, not siderite, is the dominant lithology. A chemically unstable form of pyrite (see photographs in Appendix A-3) is most abundant at the top of the unit in the Small Syncline. When fresh, some of the reactive pyrite is quite porous and some beds have a saccharoidal texture with centimetre-sized open vugs. However, the majority of the pyrite is finely laminated (see Section 8.3) and some beds have a distinct cleavage that does not extend into the surrounding rocks. The beds are commonly lensoidal over several decimetres to metres. Rare thin beds at both the top and bottom of the unit contain locally abundant doubly-terminated crystal pseudomorphs of gypsum (see Section 9.2). The very top of the Pyritic Unit contains microbial fabrics including laminites, domal and cumulate forms (see Chapter 8). Rare mudcracks were observed in outcrop. The unit is typically 30 m to 45 m thick in drillhole intersections and outcrop in the Small Syncline.

On a regional scale, the "Ore Sequence" and its lateral equivalent in the Big Syncline contain lithologies very similar to the Pyritic Unit, meaning that the Ore Sequence is underlain and flanked by pyritic sediments. The Ore Sequence in the Small Syncline averages 24 m thick and consists of thinly bedded to laminated galena, sphalerite and pyrite. The inter-ore sedimentary rocks are highly carbonaceous shales, bedded barite, dolomitic and sideritic siltstones, claystones, minor sandstone and rare intraformational breccia/conglomerate. There is a systematic lateral lithological variation within the Ore Sequence as the abundance of barite increases on the flanks on the syncline (see palinspastic reconstructions in Section 10-5). Some of the argillaceous and carbonate lithologies are rhythmically bedded, resembling tidalites (see Section 5.4).

Few of the so-called inter-ore breccias are true sedimentary breccias. Those that are occur as matrix-supported breccia and conglomerate beds less than 40 cm thick. They cannot be correlated laterally for more than a few tens of metres despite good drilling control. Distinctive pink feldspar-chert beds have been referred to as "tuffs" (see Section 11.6). Microbial fabrics, including digitate forms, and thin beds of acicular crystal pseudomorphs and moulds can be traced over the eastern limb of the Small Syncline (see Section 9.2.1). In outcrop, the Ore Sequence is a highly ferruginous chert ridge containing pods of barite. The lateral equivalent of the Ore Sequence in the Big Syncline is locally highly carbonaceous and pyritic. It contains bedded barite and variably dolomitic siltstones and claystones. The surface expression of the Ore Sequence Equivalent is more subdued to the west, reflecting a decreasing amount of chert in that direction.

Big Syncline		Small Syncline				Tom Cat, LA64, LA65		This Study
Placer (1974)		Amade (1986)		Hancock & Purvis (1990)		Donaldson (1985)		
Upper Siltstone Unit	>60	Not Present		Not Present		Conglomerate Unit	>50	Upper Clastic Unit
Upper Sandstone Unit	50 (0-80)					Graded Unit	60	
Dolomitic Shale Unit	90 (60-120)	Upper Carbonaceous Shales	120 (100-150)	Upper Carb. Shale	120	Upper Siltstone	110	
Upper Pyritic Unit	80 (40-120)	Upper Pyrite Cyclic Unit	120 (90-170)	Cyclic Unit	120			
Middle Siltstone Unit	60 (40-130)	Lower Carbonaceous Shales	Not Stated			Cyclic Unit	120	Cyclic Unit
		Massive Shale Unit	4 (1-5)	Massive Unit	4			
Ore Horizon	30 (5-35)	Ore Beds	24 (0-45)	Ore Horizon	24			Ore Sequence/ Equivalent
Lower Pyritic Unit	70 (25-80)	Sulphide Unit	30 (15-80)	Pyritic Unit	30	Massive Pyrite	>15	Pyritic Unit
Lower Siltstone Unit	>150	Lower Siderite Unit	20 (13-47)	Lower Sideritic Unit	20			Lower Carbonate Unit
		Lower Dolomite Unit	>100	Lower Dolomitic Unit	>100	Laminated Unit	75	
		Lower Siltstones	>200	Lower Siltstone Unit	>200	Lower Siltstone	>265	
Undifferentiated								

Table 3-3: Lithostratigraphy of the upper Lady Loretta Formation in the vicinity of the Lady Loretta mine. Thicknesses shown in metres are the average; ranges are given in brackets.

The "Cyclic Unit" averages about 120 m thick and contains the same lithologies as the inter-ore sedimentary rocks with proportionally more and thicker fine-grained sandstone beds. Bedded barite is conspicuously absent. This unit is sedimentologically indistinguishable between the two synclines and similar lithologies occur in the Tom Cat area. One important lithological difference is the siderite and ankerite that occurs in the lower-most Cyclic Unit overlying ore in the Small Syncline. As pointed out by McGoldrick *et al.* (1995) this was recognised by Carr (1984) but is not mentioned in the description of the deposit by Hancock and Purvis (1990). Carr (1981) described the non-random arrangements of sandstone, siltstone, pyrite and carbonaceous shale beds from the Small Syncline. This is described in more detail in Appendix A-10.2. Ripple cross lamination, small scale trough crossbeds, convolute lamination, small slumps (<10 cm) and flame structures occur sporadically throughout.

The "Upper Clastic Unit" is highly lithologically variable laterally but is a consistently overall coarsening-up package, almost devoid of carbonaceous beds. It could be assigned to the transition zone to Shady Bore Quartzite. In the Tom Cat area, a series of fining-up graded units is overlain by conglomerate. Drillholes in the Big Syncline intersected fine to medium grained sandstone, dolomitic and non-dolomitic siltstone and silty dolostone. Clastic to slightly dolomitic siltstone and sandstone are conspicuous in outcrop in the centre of the Big Syncline. The lower-most Upper Clastic Unit in the Big Syncline is less carbonaceous and more dolomitic that in the Small Syncline. Many of the sandstones contain a significant proportion of rounded sand-sized carbonate grains. Some of the coarser phases are micaceous. Wave ripples, trough crossbedding and fining-up cycles occur sporadically at the base of the unit and become more common towards the top. Carr (1981) described the sandstone as "commonly oolitic" but few ooids are preserved, resulting in oomoldic porosity. A notable exception is a thin silicified ooid grainstone identified in outcrop and several drillholes (see Chapter 6). Oncoids have also been reported (Carr, 1981). Halite moulds were identified in outcrops of sandstone from the Big Syncline (see Section 9.4). Disseminated and thinly bedded pyrite occurs near the base of the unit. The upper portion of the Upper Clastic Unit is absent in the Small Syncline, presumably having been eroded during the Cambrian.

3.4 REGIONAL STRUCTURAL SETTING

3.4.1 Regional Structural Geology

The exposed Proterozoic rocks of northwest Queensland have been divided into a number of structural domains. Figure 3-8 shows the subdivisions of the tectonic framework favoured by different authors. Deformation increases from northwest to southeast. This is reflected in the plethora of sub-domains (inlier, ridges, basins, sub-basins, troughs, platforms, shelfs, blocks, arches, belts and zones) mapped in the southeast around Mount Isa (see Blake *et al.*, 1990). Metamorphic grade also increases to the southeast, from Palaeoproterozoic rocks thermally immature for oil generation in the Bowthorn Block to greenschist and amphibolite facies metamorphism in parts of the Cloncurry Orogen.

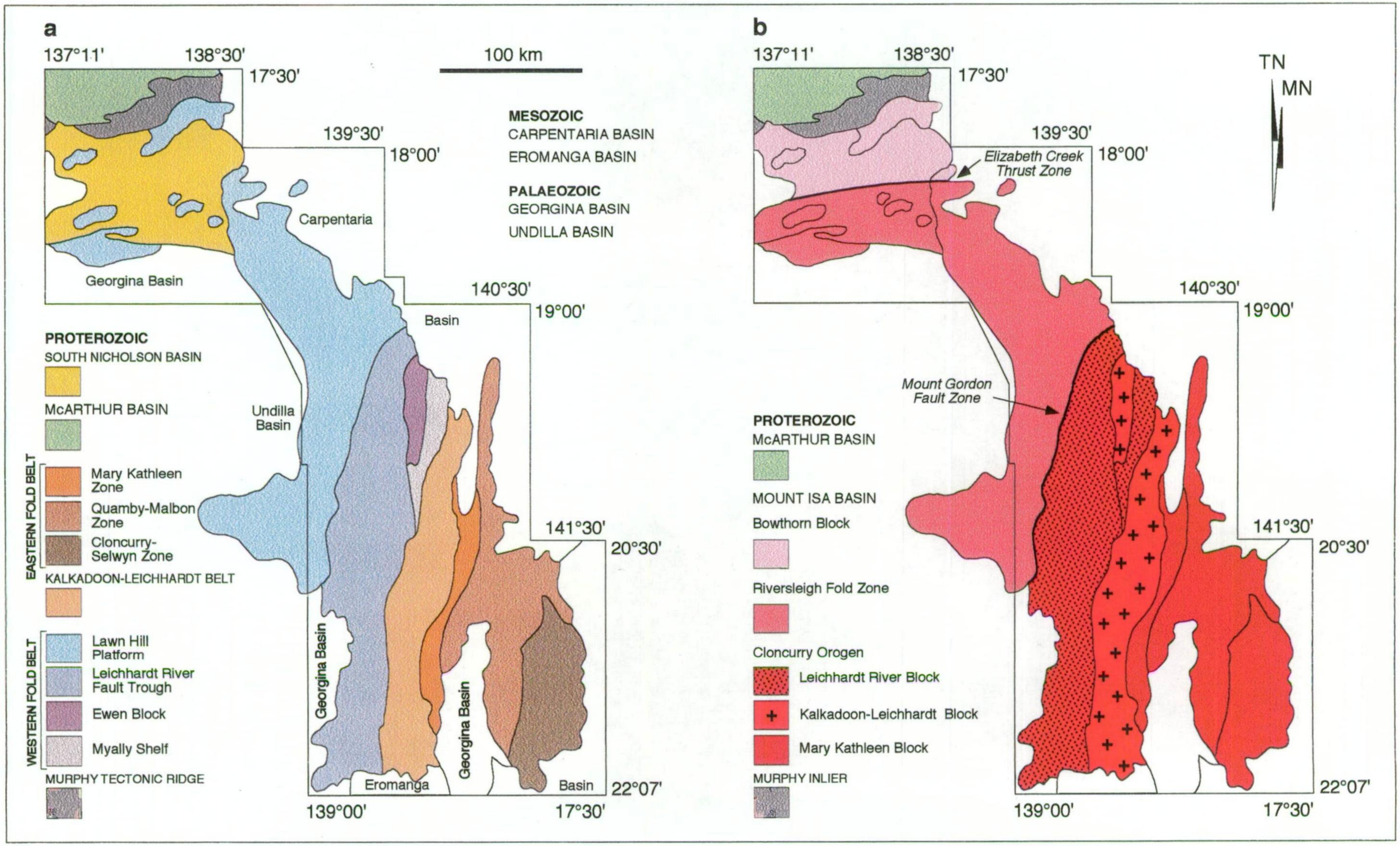
3.4.2 Nature and Timing of Orogenies and Granitoid Emplacement

Several tectono-stratigraphic cycles have been documented by O'Dea *et al.* (1995). The first cycle, correlated with the Barramundi Orogeny of Etheridge *et al.* (1987), is dated at about 1870 Ma to 1850 Ma and deformed what Blake *et al.* (1990) termed basement. Felsic volcanism and some granite emplacement (*e.g.* Yeldham Granite - 1820 Ma) accompanied this phase or followed shortly after. This interval of volcanism and compressional orogenesis can be recognised in other Australian Proterozoic rocks and correlated with the Wopmay and Trans-Hudson orogenies of Canada and the Sveco Fennian orogeny in the Baltic Shield (O'Dea *et al.*, 1995).

Following the Barramundi Orogeny, the southern portion of the region underwent a long and complex history of intermittent rifting and thermal subsidence involving at least three major episodes (O'Dea *et al.*, 1995). The first of these was synchronous with the deposition of the Bigie Formation and Peters Creek and Fiery Creek Volcanics (Betts *et al.*, 1996). The volcanics in this phase are dated at 1726 and 1709 Ma (Page and Sweet, in press). The Weberra Granite (1698 Ma), Sybella Batholith (1671 Ma) and Carter's Bore Rhyolite (1678 Ma) may have been emplaced during, or immediately after, this phase. Some fault activity appears to have persisted during deposition of the Surprise Creek, Torpedo Creek and lower Gunpowder Creek Formations (Keele, 1994). Elsewhere, there is convincing evidence of renewed tectonic activity at Gunpowder time (Scott *et al.*, 1996). Regional compressive deformation took place during the Isan Orogeny, between about 1620 Ma and 1500 Ma. This basin inversion and regional wrenching resulted in predominantly north-south structural trends including upright folding, high and low angle faulting, and regional low-pressure metamorphism in the south (O'Dea *et al.*, 1995). Considerable, largely strike slip, faulting and fault reactivation has taken place since 1550 Ma. The NNE trending faults are sinistral; the NNW are dextral (Blake *et al.*, 1990; Blake and Stewart, 1992).

Uplift and erosion are believed to have occurred prior to the Cambrian but several of the major faults offset Cambrian rocks and so must be younger. Younger periods of uplift and exhumation have been inferred from apatite fission track studies. These studies were interpreted to suggest a relatively rapid exhumation of over 2 km of stratigraphy associated with the mid-Carboniferous Alice Springs Orogeny (Spikings *et al.*, 1996). The flat-lying Jurassic to Cretaceous cover contains very few faults.

Figure 3-8: Structural domains as recognised by different authors. (a) Some of the terminology used in Blake et al. (1990) and O'Dea et al. (1995). (b) A simplified scheme proposed by McConachie et al. (1993) to avoid misleading terms such as "Inlier" and "Platform".



a
137°11'
138°30'
100 km
17°30'
MESOZOIC
CARPENTARIA BASIN
EROMANGA BASIN
139°30'
18°00'
PALAEOZOIC
GEORGINA BASIN
UNDILLA BASIN
Carpentaria
Georgina Basin
140°30'
19°00'
Basin
PROTEROZOIC
SOUTH NICHOLSON BASIN
McARTHUR BASIN
Undilla Basin
EASTERN FOLD BELT
Mary Kathleen Zone
Quamby-Malbon Zone
Cloncurry-Selwyn Zone
KALKADOON-LEICHHARDT BELT
141°30'
20°30'
WESTERN FOLD BELT
Lawn Hill Platform
Leichhardt River Fault Trough
Ewen Block
Myally Shelf
MURPHY TECTONIC RIDGE
Georgina Basin
Georgina Basin
Eromanga
Basin
22°07'
139°00'
17°30'
b
137°11'
138°30'
17°30'
TN
MN
139°30'
Elizabeth Creek Thrust Zone
18°00'
140°30'
19°00'
Mount Gordon Fault Zone
PROTEROZOIC
McARTHUR BASIN
MOUNT ISA BASIN
Bowthorn Block
Riversleigh Fold Zone
Cloncurry Orogen
Leichhardt River Block
Kalkadoon-Leichhardt Block
Mary Kathleen Block
MURPHY INLIER
141°30'
20°30'
22°07'
139°00'
17°30'

3.4.3 Structural Geology of the Lady Loretta Formation

The Lady Loretta Formation and other McNamara Group rocks are folded into anticlines, synclines and domes and are affected by both regional and local faulting (Figure 1-3).

In the Bowthorn Block, McConachie (1993b) interpreted the earliest structural features as normal faults subsequently reactivated as thrusts. Near the Lady Loretta mine, the earliest generation of faults are thought to be east-west trending (*e.g.* Redie Creek Fault and Carlton Fault Zone). The present displacement on these faults is down to the south by several hundreds of metres. Later regional faults in the Lawn Hill area tend to be orthogonal NNW (*e.g.* Termite Range Fault) and SSE (*e.g.* faults at Kamarga Dome). The Termite Range Fault can be traced for over 100 km and both strike-slip and vertical displacements in excess of one kilometre have been calculated (Hutton and Wilson, 1984). The present eastern distribution of the Lady Loretta Formation is controlled by the Mount Gordon Fault Zone which also may have a considerable lateral (?dextral) component.

In the area around and including the Lady Loretta ore body, many of the tighter folds trend north-south parallel to the larger faults. The ore body is within this north-south corridor of tighter folding bounded by Russell Creek and Western Border Faults, originally interpreted as a graben, and now termed the Paradise Creek high strain zone (Dunster and McConachie, in press*; "Lady Loretta high strain zone" in Keele, 1994; Keele *et al.* 1996). Keele (1994) also recognised an east-west trending regional axis; north of which, folds plunge to the north and south of which, folds plunge south. This axis passes just south of the Lady Loretta mine. The axis is offset across the Paradise Creek high strain zone, indicating that it was affected by all subsequent deformations.

3.4.4 Syn-Sedimentary Faulting in the Lady Loretta Formation?

The presence of syn-sedimentary faulting in the Lady Loretta Formation has been an important element of genetic models based on the Lady Loretta ore body, and considerable exploration effort has been directed toward finding syn-depositional or growth faults in the Lady Loretta Formation. The current study examined several possible examples cited in unpublished company reports as well as potential growth faults shown on the published maps and similar features identified on airphotos.

Hancock (1990) interpreted mapping by Berg (1986) to indicate that both the Termite Range Fault (288500E 7883600N) and an un-named northeast-southwest splay (293000E 7893000N) controlled the facies distribution, primarily the carbonaceous shale, in the Lady Loretta Formation. Other investigations in the same area by M. Jones (1993) interpreted the "basal breccia" between the Lady Loretta and Esperanza Formations as evidence of localised syn-sedimentary uplift and erosion along an un-named north-south fault (298500E 7874000N). Collaborative field work with P. Betts (Monash Uni.) and D. Scott (AGSO) demonstrated considerable mismapping in this area and recognised several faults but none of these faults were likely to have been active during Lady Loretta deposition. The "basal breccia" discussed by M. Jones (1993) is not present as mapped and is now interpreted as regolith (see Chapter 12).

Pringle and David (1983) suggested that Archie Fault on Kamarga Dome may have been syn-sedimentary and responsible for localised sandy facies in the Lady Loretta Formation. The present study demonstrates that it is possible to correlate the sandstones across Archie Fault and that there are no unusual thickness changes or facies variations.

Several unpublished company reports drew attention to an apparent dramatic thickness variation in the Esperanza and Lady Loretta Formations across an un-named fault on the southwestern flanks of Kamarga Dome shown on the published 1: 100 000 scale Lawn Hill Region map (272000E 7925300N). Independent mapping by the author and North Exploration demonstrated that the apparent thickness variation is due to a mismapping of the contact between the formations.

In summary, there is no clear evidence of large-scale syn-sedimentary faulting during deposition of the Lady Loretta Formation.

3.5 STRUCTURAL SETTING OF THE LADY LORETTA ORE BODY

The Lady Loretta ore body is in the keel of a faulted, doubly-plunging syncline. This syncline is one of many folds in a prominent north-south high strain zone. There are numerous faults in the vicinity of the mine and it is important to note that much of the outcrop of the Ore Sequence Equivalent is faulted into place and that the basal portion of the Lady Loretta Formation has been faulted out beneath the mine sequence. A reassessment of the local structural geology was necessary to establish the original sedimentary facies distributions and their true stratigraphic thicknesses so a palinspastic reconstruction could be undertaken.

The suggestions that Carlton Fault Zone was syn-sedimentary and/or a conduit for mineralising fluids (*e.g.* Carr, 1981) were critically examined.

3.5.1 Faulting

The major surface faults in the vicinity of the ore body are shown in Figure 3-9.

Western Border Fault and Russell Creek Faults

The north-trending Western Border Fault juxtaposes the Lady Loretta Formation against Cambrian rocks and forms one side of a high strain corridor, suggesting that it may be a basement-controlled feature. Van Dijk (1991) interpreted it as a "transpositional thrust", whereas Daneel (1992) believed it to be a curvi-linear, sub-vertical normal fault. Interpretation of geophysical data suggests that the fault may dip steeply to the west (Russell *et al.*, 1976), making its present sense a thrust. However, Keele *et al.* (1996) showed the Western Border Fault as dipping steeply to the east and believed that it is "made up of a combination of intra-rift and rift-border faults." The surface expression of the fault is a brittle shear zone in Cambrian carbonates and a much broader zone of large anastomosing pods of vein quartz (visible on airphotos) in the Proterozoic rocks. Similar pyritic and carbonaceous facies that host the ore are present in the subsurface on both sides of the Western Border Fault. Their lateral offset and the relationship to east-west faults may be interpreted to indicate a sinistral component to the last movement.

The current study identified a hither-to unknown splay of the Western Border Fault along the western limb of the Greater Loretta Syncline (296300E 7808500N) with the result that the Esperanza and Lady Loretta Formations are in faulted, rather than conformable, contact in this area.

The north-trending Russell Creek Fault is believed to be a normal fault that forms the western boundary of the high strain zone identified by Keele (1994). The present sense of the fault is west down and the throw is variable because it is partitioned by at least two east-west offsets. The rocks on the western side of the fault are folded in a major north-south syncline, only a portion of which is shown on the published 1:100 000 scale map. An interpretation of the magnetics by Keele *et al.* (1996) suggested that there are (?were) unlikely to be any volcanics at depth west of Russell Creek Fault. This may be interpreted to indicate that the fault is an older structure reactivated during the Isan Orogeny.

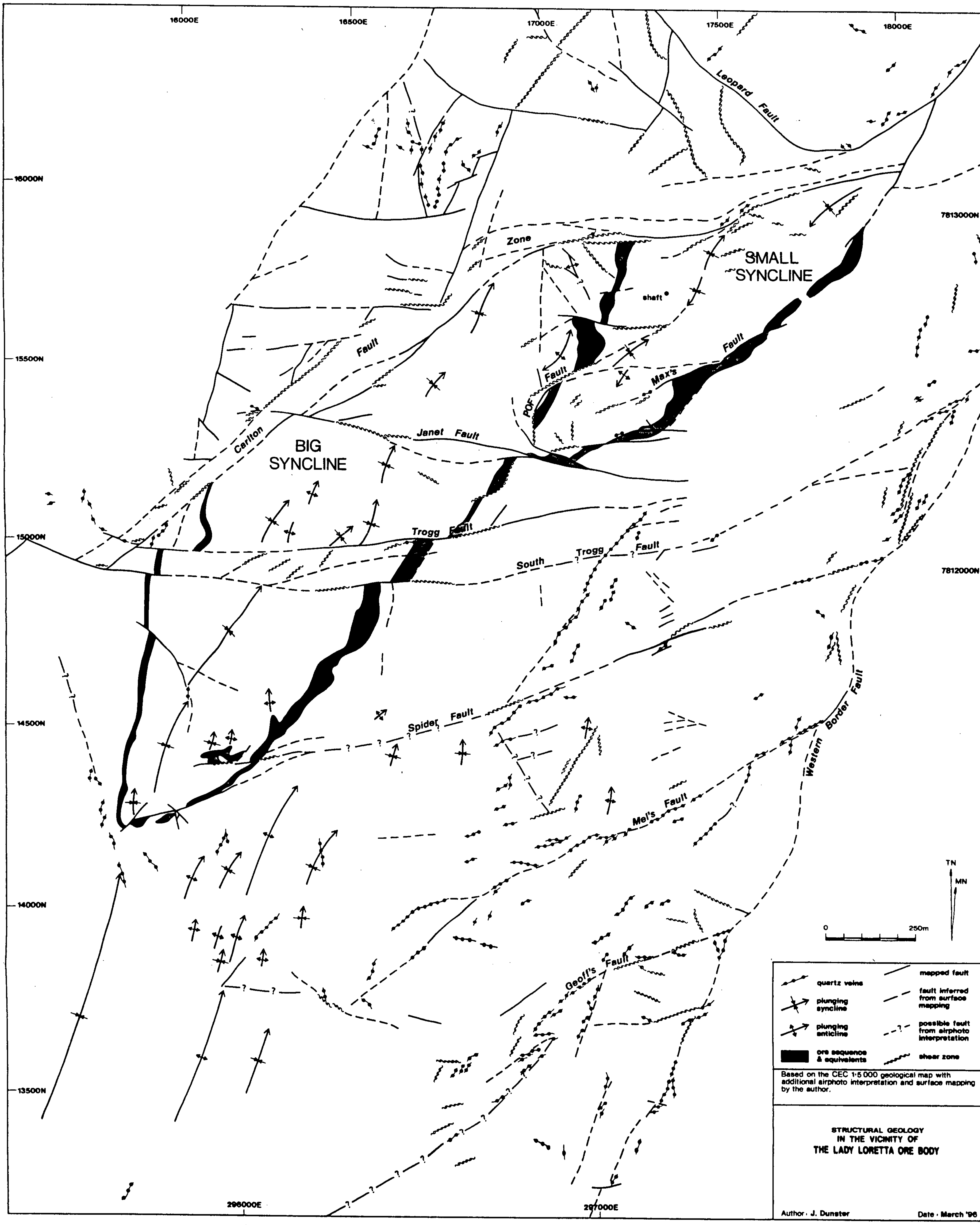
Leopard Fault

The west- to northwest-trending Leopard Fault, juxtaposes the Surprise Creek Formation with the Esperanza and ?Paradise Creek Formations. It's present sense is a curved thrust. Keele (1994) suggested that the Leopard Fault and a segment of the Western Border Fault were active in concert during the deposition of the Torpedo Creek Quartzite Formation and the overlying Gunpowder Creek Formation. The Leopard Fault was later inverted during the Isan Orogeny (Keele, 1994).

Carlton Fault Zone - was it Syn-sedimentary? Was it a Conduit for Mineralising Fluids?

The Carlton Fault Zone is a curvilinear NE trending normal fault zone some 200 m wide on the ground characterised by mechanical brecciation and local quartz veining with little evidence of hydraulic fracturing. The upper Lady Loretta Formation is exposed on the southern side, juxtaposed with the lower Lady Loretta Formation, Esperanza and ?Paradise Creek Formations on the northern side. A vertical throw of at least 1500 m was determined. A dextral component of movement was also identified on airphoto interpretations by Lemcke (1986). This was subsequently contradicted by Harris (1993) who interpreted a sinistral component. Neither could be confirmed during the present study as no diagnostic features were found in outcrop and re-interpretation of the aerial photography is equivocal. The fault plane is steeply dipping from 55° towards the southeast in outcrop to near vertical in the shallow subsurface. Underground drilling results indicate that the fault soles-out to the southeast at a depth of approximately 500 m in drillhole 2420P121 and at 450 m in 2480P128. These holes intersected so-called "silica dolomite" and trace Cu mineralisation over 80 m below the Zn-Pb-Ag ore. This is most likely to be brecciation and alteration associated with Carlton Fault and, contrary to earlier interpretations (*e.g.* Carr, 1981), may not be in the Lady Loretta Formation. A number of

Figure 3-9 (fold-out): Structural geology in the vicinity of the Lady Loretta ore body.


16000E
16500E
17000E
17500E
18000E
16000N
15500N
15000N
14500N
14000N
13500N
7813000N
7812000N
296000E
297000E
Leopard Fault
Zone
SMALL SYNCLINE
shaft
Fault
Max's Fault
POF Fault
Carlton Fault
Janet Fault
BIG SYNCLINE
Trogg Fault
South Trogg Fault
Spider Fault
Western Border Fault
Mel's Fault
Geoff's Fault
TN
MN
0
250m
quartz veins
plunging syncline
plunging anticline
ore sequence & equivalents
mapped fault
fault inferred from surface mapping
possible fault from airphoto interpretation
shear zone
Based on the CEC 1:5 000 geological map with additional airphoto interpretation and surface mapping by the author.
STRUCTURAL GEOLOGY
IN THE VICINITY OF
THE LADY LORETTA ORE BODY
Author · J. Dunster
Date · March '96

offsets of the fault zone have been mapped, on the basis of both surface expression and underground drilling.

Most previous workers (*e.g.* Alcock and Lee, 1974; Large, 1980; Carr, 1981: Lemcke, 1986; Hancock and Purvis, 1990) believed that subsidence in the Small Syncline was controlled by penecontemporaneous faulting on the Carlton Fault Zone. All previous reports state that the Ore Sequence is offset by the Carlton Fault Zone and several authors postulated that the fault was the feeder for the mineralising fluids responsible for the Lady Loretta ore.

The main lines of evidence used to argue that the Carlton Fault Zone was syn-sedimentary were:

- that highly carbonaceous pyritic facies were considered to be deep water deposits unique to the vicinity of the mine and were thought to have deposited in an active half-graben bounded by the fault in the north
- thickening of the Lady Loretta Formation toward the fault
- the presence of talus breccias and debris flows in the ore host sediments
- sedimentary slumps and palaeocurrents in the Small Syncline directed away from the fault.

The Carlton Fault Zone truncates the major upright folds and its present sense, at least, indicates a significant movement post-folding. There is no evidence for an earlier movement, although this possibility cannot be discounted. As discussed at length elsewhere in this thesis, the highly carbonaceous and pyritic facies that host the Lady Loretta ore body extend much further to the east from the Carlton Fault Zone than previously thought. Similar facies occur elsewhere in the formation (*e.g.* Carrier, Johnson Creek) where there is no suggestion of facies control by syn-sedimentary faults. There is no indication that the Lady Loretta Formation or any of its lithostratigraphic subdivisions thicken toward the fault. Nor are there any lateral facies changes that would be associated with a growth fault. Detailed studies of the extensive underground core by both Aheimer (1994) and the author could not confirm that sedimentary breccias within the Ore Sequence were debris flows related to the Carlton Fault. The previous interpretations of palaeocurrents directed away from the fault are disputed (see Section 5.5). Thus, there is no convincing evidence that the Carlton Fault Zone was active during the deposition of the Lady Loretta Formation.

Previous studies that suggested that the Carlton Fault Zone was a fluid feeder were based on supposed increases in the following toward the fault:

- ore grades
- the Cu, Ag and Zn tenor
- the abundance of barite
- radiogenic isotopes, especially $^{207}Pb/^{206}Pb$.

Even cursory examination of the sections shown in Amade (1986, his Figure 9) and the more detailed underground mine plan sections reveal that the highest ore grades (the direct shipping ore) are in the keel of the Small Syncline and that this is not related in any way to the Carlton Fault Zone. The fault offsets only a small fraction of the margin of economic ore. The Ag grade across the ore body, as mapped by Carr (1981) and Amade (1986), shows no obvious relationship to the Carlton Fault Zone. Detailed quantitative work by Aheimer (1994) demonstrated that neither the Cu tenor nor the Zn number (100Zn/(Zn + Pb)) increase toward the fault. Barite *is* abundant on the western limb of the Small Syncline adjacent to the fault zone but is not obviously associated with proximity to the fault in the Big Syncline. The Ba% distribution map shown in Amade (1986, his Figure 12) does not support the contention that barite increases toward the Carlton Fault Zone. The lead isotopic ratios reported in Vaasjoki and Gulson (1985) previously have been interpreted as showing a spatial relationship to the Carlton Fault Zone. However, Vaasjoki and Gulson (1985) themselves inferred no such relationship; merely stating that one sample collected from the vicinity of the fault had the most radiogenic ratio encountered in their study. In fact, they also noted a converse relationship, with seven of twelve samples containing the least radiogenic lead coming from the western limb of the Small Syncline adjacent to the fault zone. Correlation coefficients can be interpreted to indicate that there is no positive relationship between $^{207}Pb/^{206}Pb$ and the distance from the Carlton Fault Zone using either the present geometry ($r^2 = 0.04$) or Carr's (1981) unfolded syncline ($r^2 = 0.06$). Thus, none of the evidence previously used to argue that Carlton Fault was a conduit for mineralising fluids can be justified.

Max's Fault

Max's Fault is a prominent northeast-trending surface feature on the eastern limb of the Small Syncline. It is noteworthy that Max's Fault is the only fault in the vicinity of the ore body that exhibits significant hydraulic fracturing. The fault also produced plastic deformation of the barite-rich zones in the equivalent of the Ore Sequence at the surface. There are alternative extrapolations of its surface expression, mostly based on airphoto interpretation (*cf.* Russell *et al.*, 1976; Amade, 1986; Hancock and Purvis, 1990; Daneel, 1992). Several of these are not consistent with interpretations based on the underground drilling. Note that on the author's map (Figure 3-9), Max's Fault is a compound fault system that follows the surface expression of the Ore Sequence Equivalent along part of the eastern limb of the Small Syncline and is associated with a major east-west trending splay.

In the shallow subsurface, Max's Fault is steeply northwest-dipping. It offsets ore on the northwest flank of the syncline, becomes an axial plane fault through the Ore Sequence with the east side downthrown, and soles-out at depth. Max's Fault is believed to post-date and offset the Carlton Fault Zone on the lower western limb of the Small Syncline and it may merge with Pof Fault at depth.

Hancock and Purvis (1990) cite an apparent dip displacement of 20 to 50 m; varying along strike. The underground mine sections show >40 m of vertical offset of ore north of drilling grid line 3000 and this can be confirmed by the offset of other stratigraphic markers recognised during the present study. These figures were used in palinspastic reconstructions. Carr (1981) and Hancock and Purvis (1990) also noted that there could also be a significant strike slip component. This could not be quantified during the present study.

Pof Fault

Pof Fault is a complex curved north- to west-trending sub-vertical system of shears and fractures with several splays. It offsets outcrop of the equivalent of the Ore Sequence in the nose of the Small Syncline. In interpretations by Amade (1986) and Hancock and Purvis (1990), Pof Fault is shown as part of the Syncline Dividing Fault. Lee (1972) interpreted a dextral component. The present study, based on surface mapping and reinterpretation of stratigraphy from cores, is in agreement with the orientation shown by Daneel (1992). He suggested both dextral and vertical displacements (both <20 m) and that a northeasterly trending splay may continue as an axial plane fault to the Small Syncline. The subsurface expression is poorly constrained because of a lack of drilling.

Janet, Trogg , South Trogg, Spider, Mel's and Geoff's Faults

These faults are all subparallel steeply dipping east-west trending normal faults, downthrown to the south. There may be a dextral component to the offset of the equivalent of the Ore Sequence by Trogg and South Trogg Faults. Janet and Trogg Fault may merge in the east. Slickenlines and quartz fibres in Mel's Fault can be interpreted to indicate a nearly horizontal component of movement and the offset of dolomitic units indicates a dextral sense. These faults are all associated with an increase in quartz veining and brittle shearing to the east and share a common geometric relationship to the curvature of Western Border Fault (Figure 3-9). This may be interpreted to suggest that they acted as dextral shears during lateral movement on Western Border Fault. However, the present sense of movement on these faults is the opposite to that expected if the Western Border Fault is sinistral.

Other Significant Faults in the Subsurface

Koff Fault has only been mapped in the subsurface. It offsets the Carlton Fault Zone and is subparallel to Max's Fault and may merge with it in the south. The zone between these two faults contains intensely folded and faulted ore.

Justin's Fault is a multiple northeast trending structure in the central-northern part of the ore body. It offsets ore in the keel of the Small Syncline with a sense of down to the south. Justin's Fault is probably a splay of the Carlton Fault Zone or may actually be an offset of it.

3.5.2 Folding

The Synclines

The Greater Loretta Syncline is a compound, faulted structure (Figures 3-5, 3-9). Within it, the exposed upper stratigraphic levels of the Lady Loretta Formation adjacent to the Carlton Fault Zone are termed the Big and Small Synclines. Economic mineralisation is restricted to the keel of the Small Syncline. The Big Syncline contains a stratigraphically equivalent sequence ranging form subeconomic to barren (Figure 3-9).

The Big Syncline is asymmetric, the western limb dips steeply (70°) to the east from the surface, the eastern limb dips at about 50° northwest at the surface. The fold axis plunges 43° on 007°T in the south. Numerous small-scale northerly plunging Z-folds are developed within the eastern limb (Daneel, 1992) and complex ?parasitic folding has been mapped in outcrop to the southeast of the fold nose (Figures 3-7, 3-9).

The Small Syncline (Figure 3-10) is a northeast trending asymmetric doubly plunging fold with a subsidiary northeast trending recumbent fold between faults on the western limb. The Small Syncline plunges 13° on 033°T in the southwest. It plunges to the southwest in the northeast. This was probably caused by fault-drag on the Carlton / Leopard Faults. The ore body is located within the keel of the syncline (Figure 3-11).

These fold orientations were used to correct the palaeocurrent data derived from outcrop on the limbs of the synclines (see Section 5.5.5).

The structural relationship between the two synclines remains problematical. A Syncline Dividing Fault has been postulated; other workers have suggested a tight anticline or a combination of both folds and faults. Some elements of the Syncline Dividing Fault as shown in Hancock and Purvis (1990) are not consistent with subsurface information. Daneel (1992) believed that "the Small Syncline was originally developed as a portion of the north-easterly trending Greater Loretta Syncline, and has subsequently been partitioned, rotated and deformed by the Carlton / Leopard Fault". The possibility that the Small Syncline is a thrust repeat of the Big Syncline is not supported by the present interpretation of stratigraphy in the Big Syncline.

The current interpretation of this structurally complex area, including several hither-to unmapped faults, is shown in Figure 3-9. It suggests that the synclines are separated by a zone of multiple generations of faulting and tight folding. This is in agreement with Carr (1981) and Keele *et al.* (1996) who both documented early folds in a baritic shear zone from this area.

Folding within the Small Syncline

Lee (1972) and Daneel (1992) documented younger folds in the area bounded by the Carlton/Leopard Faults in the north and by the eastern limb of the Small Syncline in the southeast. In the subsurface, a large recumbent syncline in the Ore Sequence between Koff, Carlton and Max's Faults (line 2360) has also been attributed to a younger deformation as a result of faulting.

On a smaller scale, complex folded repetitions of the Ore Sequence which did not effect the more competent surrounding sedimentary rocks were noted during shaft sinking and underground work (Hancock and Purvis, 1990). The extensive underground cores show the same features; the more ductile ore displays several generations of folds while the thickly bedded silicified host sediments are more gently folded. This is illustrated in Aheimer (1994). Such deformation is more intense near the keel of the Small Syncline. Lee (1972) originally interpreted these features as gravity folds and sedimentary slumps directed towards the centre of a depositional basin now corresponding to the Small Syncline. These features are now reinterpreted as multiple generations of parasitic

Figure 3-10: Vertical section through the Small Syncline, modified from Hancock and Purvis (1990).

Section 2300

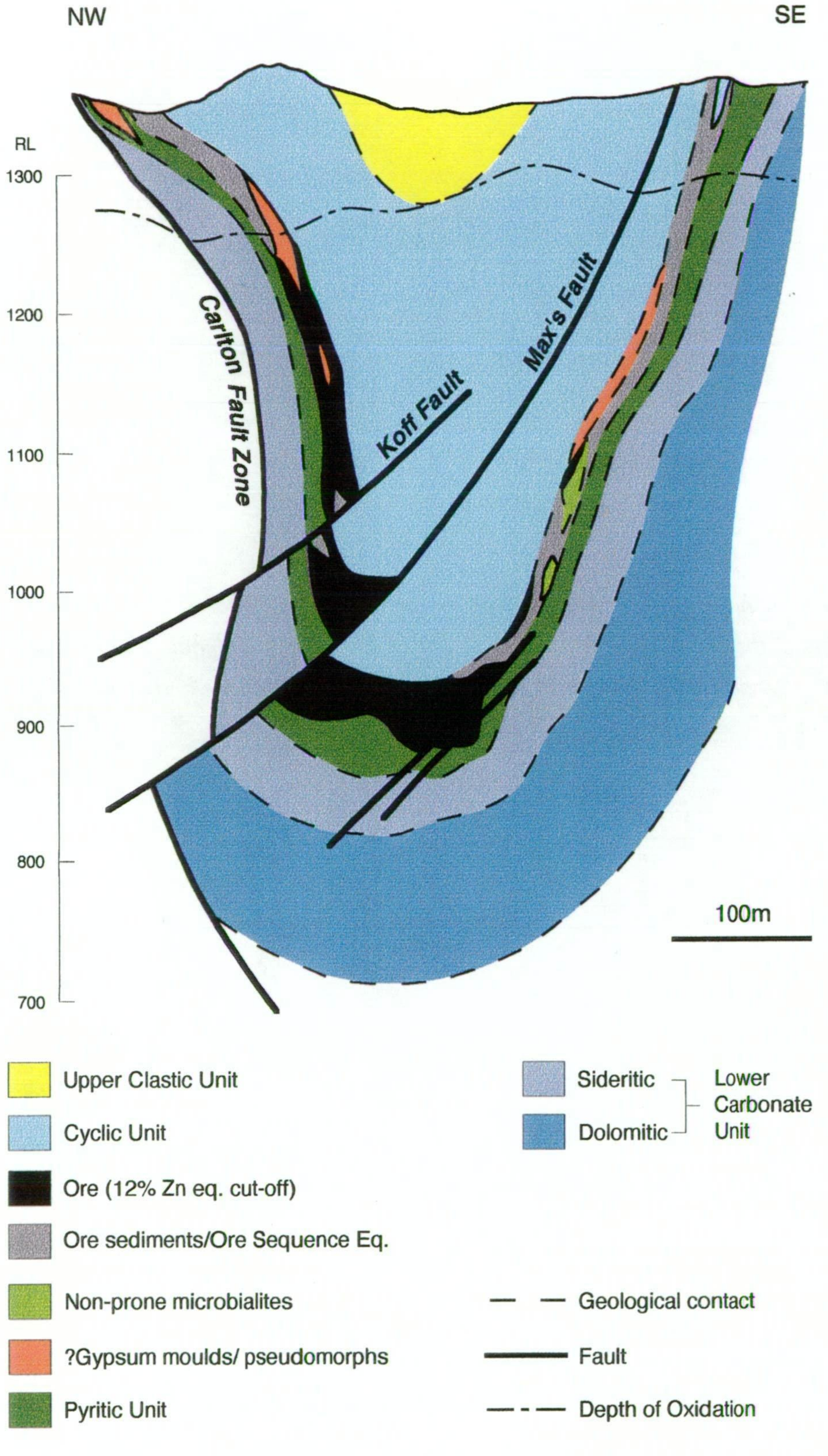
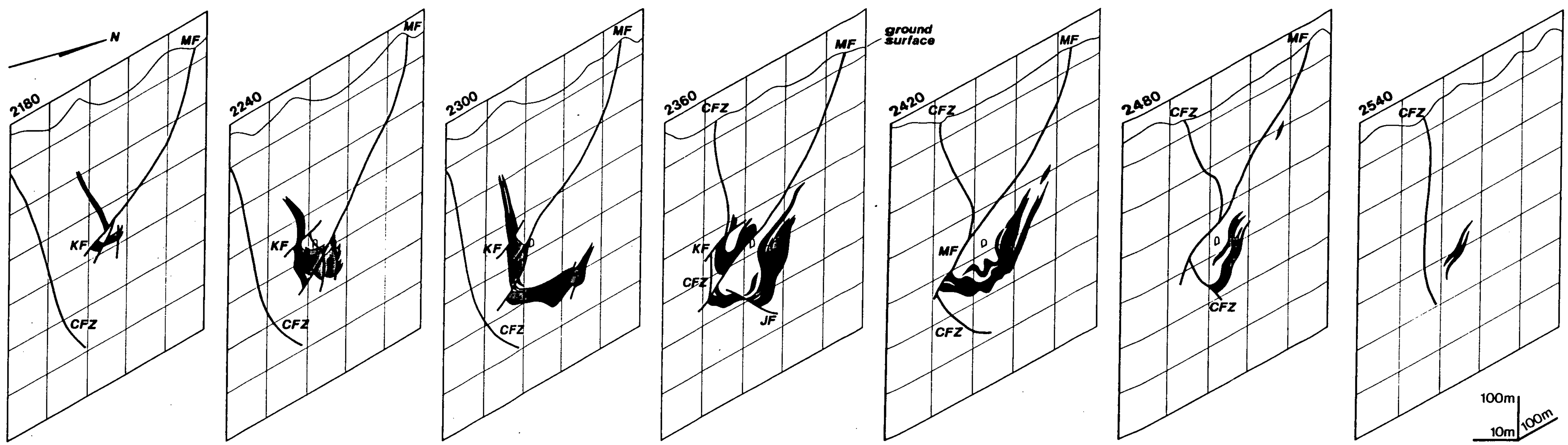


Figure 3-11: A series of vertical sections through the Small Syncline showing the structuring of the ore body as defined by underground drilling (cf. Figure 9 in Amade, 1986). MF is Max's Fault, KF is Koff Fault, CFZ is Carlton Fault Zone and JF is Justin's Fault.



N
2180
MF
KF
CFZ
2240
MF
KF
CFZ
2300
MF
KF
CFZ
2360
CFZ
MF
ground
surface
KF
CFZ
JF
2420
CFZ
MF
MF
CFZ
2480
CFZ
MF
CFZ
2540
CFZ
100m
10m
100m

folding. Spatially associated plastic and brittle deformation textures, tension gashes hosting secondary mineralisation, and folded concordant fibrous veins confirm the tectonic origin of these folds. The S and Z fold configurations on each limb probably led Lee (1972) to believe that "slumps" were directed towards the centre of the syncline. Such folding and mechanical remobilisation of ore significantly enhances the average grades in the keel of the syncline and may be responsible for producing the high-grade direct shipping ore.

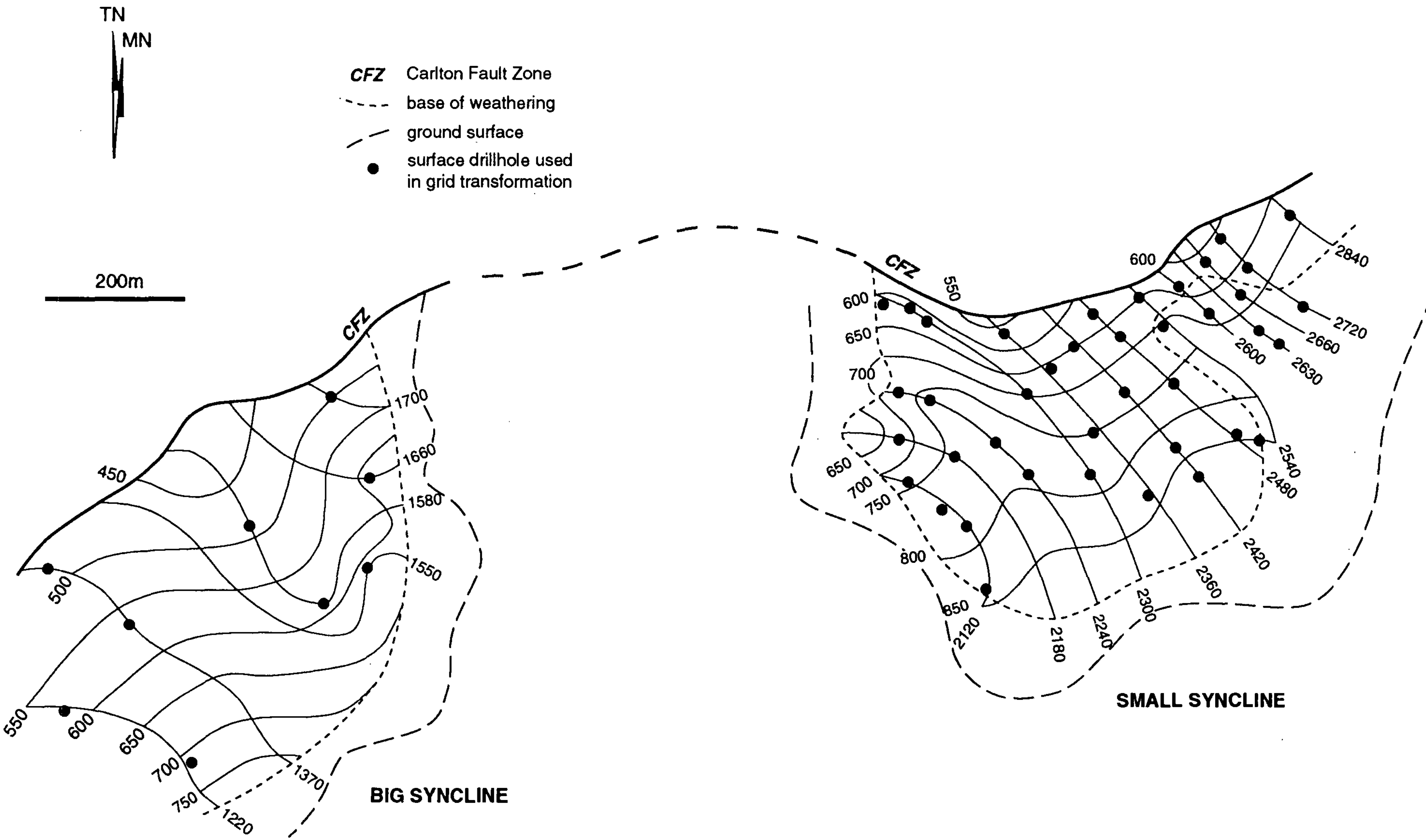
3.5.3 Techniques for Palinspastic Structural Reconstructions of the Mine Stratigraphy

Carr (1981) used a series of complex mathematical algorithms to remove the effects of faulting and unfold the synclines assuming both concentric and cleavage folding. His reconstruction calculated an original separation of between 600 and 900 m between the present erosional edges of the two synclines. The present study has accepted this but modified his internal geometry of the synclines. Depth corrections for the surface drillholes were used to transform the underground drilling grid as projected on to the top of the Ore Sequence as a neutral surface. Other modifications to Carr's (1981) reconstruction were:

- redefining the top of the Ore Sequence to be consistent with mine sections based on underground drilling and other lithostratigraphic units as defined in the current study
- the inclusion of additional faults and corrections to offsets, especially for those faults that sole-out at depth
- the inclusion of several underground drillholes omitted from the mine sections
- corrections to the trajectory of surface holes shown in Carr (1981) to be consistent with underground mine sections
- the inclusion of additional southeastern grid lines to better define the nose of the Big Syncline
- transforming the grid on selected vertical planes, at 100 m RLs from 900 to 1300 m as shown on the underground mine sections; this presents a more accurate representation than the vertical sections shown in Aheimer (1994) or Carr (1981) in which drillholes have been restored to vertical and are assumed to be straight line projections from the neutral surface.

The transformed grid is shown, greatly simplified, in plan in Figure 3-12 and the resulting palinspastic reconstructions are shown as Figures 10-4, in Section 10.5.2.

Figure 3-12: Palinspastic plan map of the unfolded Big and Small Synclines showing the transformed drilling grid projected onto the top of the Ore Sequence. The surface drillholes used to affect the conversion are plotted.



TN
MN
CFZ Carlton Fault Zone
base of weathering
ground surface
surface drillhole used in grid transformation
200m
CFZ
450
500
550
600
650
700
750
1700
1660
1580
1550
1370
1220
BIG SYNCLINE
CFZ
550
600
650
700
650
700
750
800
850
2120
2180
2240
2300
2360
2420
2480
2540
2600
2630
2660
2720
2840
SMALL SYNCLINE

Chapter 4 - Mineralogy, Isotopes and Geochemistry

4. MINERALOGY, ISOTOPE AND GEOCHEMISTRY OF THE LADY LORETTA FORMATION

4.1 INTRODUCTION

This chapter is an introduction to the chemistry and mineralogy of the Lady Loretta Formation. The trace element geochemistry of a well-preserved ooid pisoid grainstone is examined to determine the original carbonate mineralogy. The various forms of diagenetic carbonate associated with the ore host sediments are compared with lithologically similar packages from unmineralised areas elsewhere in the formation. A brief summary of the isotope geochemistry is presented and the significance of clay mineralogy, silicification and the TOC content are discussed in the context of mineralisation. The composition of the Lady Loretta ore and potential pathfinder elements are reviewed.

4.2 CARBONATE COMPOSITION

The carbonate mineralogy and trace element geochemistry of the Lady Loretta Formation have been analysed at several localities:

- core from drillhole Amoco 83-5
- outcrop at section KD4 Kamarga Dome, where an ooid pisoid grainstone containing unusually large coated grains was studied in detail to determine the primary carbonate composition
- core from the Lady Loretta ore body
- core and outcrop from Johnson Creek, near the base of the formation
- core from the Carrier area.

These localities span the range of stratigraphic and lateral distribution of the formation. The last two locations contain highly pyritic and carbonaceous lithologies and were included as possible analogues for the Lady Loretta SSHBM host sediments.

The results are discussed in detail in Appendix A-8 and summarised here.

On the basis of trace element geochemistry and microstructure, the ooid pisoid grainstone is unlikely to have been primary aragonite. This is in marked contrast to morphologically similar coated grains from the Neoproterozoic that are unanimously interpreted as having had an aragonitic precursor (see Section 6.4.5).

The present carbonate composition of the Lady Loretta Formation can be locally highly variable. In the vicinity of the ore body, carbonates include dolomite, ferroan dolomite, ankerite, siderite, magnesian siderite, sideroplesite and pistomesite. The current study demonstrated that such diversity is not unique to the ore body. Carbonates associated with pyritic and carbonaceous lithologies at both Carrier and Johnson Creek consist of similar mineral assemblages. Of particular note is the wide spread in $MgCO_3$/ $MnCO_3$ observed in all these locations. Although the Mn content of dolomite has been interpreted as a vector to mineralisation (Large *et al.*, 1995), the present study detected Mn-enriched carbonates in similar host rocks and suggests that Mn-enrichment may not be related to base metal mineralisation. Furthermore, on the basis of low correlation coefficients, there does not appear to be any statistical relationships between the generally low Zn, Pb, Cu and Mn in these carbonates away from the mine. Thus, it is unlikely that the same fluid was responsible for the Mn alteration and metal enrichment.

4.3 CARBON AND OXYGEN ISOTOPES

Several carbon and oxygen isotope studies of the Lady Loretta Formation carbonates have been undertaken:

- whole rock powders of dolomites from drillhole Amoco 83-5 were analysed by both CODES and NABRE
- whole rock studies from cores at the Lady Loretta ore body (Large *et al.*, 1995).

The present study sampled much more selectively by using a dental drill and analysed:

- microbial material and cement from near the contact of the Esperanza and Lady Loretta Formations in drillhole CM35
- ooids and cement from outcrop of an ooid pisoid grainstone in the KD4 section at Kamarga Dome (as described above).

The methods, results and interpretation are described in detail in Appendices A-6, A-7 and A-9. The whole rock analyses from Amoco 83-5 showed relatively little isotopic variation stratigraphically over the interval analysed. Both the microbial material and cement from the base of the formation have very depleted oxygen isotopes. There is no significant difference between the isotopic content of the coated grains and the bulk composition of the ooid pisoid grainstone. Palaeothermometry using the oxygen isotopes of the least-altered dolomite can be interpreted to suggest tropical temperatures at the time of deposition, but the author cautions against such a simple interpretation (see Appendix A-9).

Studies by Large *et al.* (1995) documented a systematic variation in the stable isotopes in carbonates within the alteration halo around the Lady Loretta ore body. The inner zone siderite has more enriched oxygen isotopes and depleted carbon isotopes relative to the outer zone dolomite. Dolomite from the mine has more depleted oxygen and carbon isotopes than away from the vicinity of the mine. Modeling, assuming a bicarbonate fluid composition, indicates that dolomites were formed from a fluid of about 50°C, suggesting either a meteoric or evaporated seawater source (Large *et al.*, 1995). The siderite and ankerite could both have formed from a single meteoric fluid at temperatures of near 100°C (Large *et al.*, 1995). Siderite could not have precipitated from the same fluid that formed the dolomite. The work by Large *et al.* (1995) demonstrated that systematic variation in stable isotopes can be used as a vector to mineralisation at Lady Loretta mine. Although not stressed in their work, there is a strong mineralogical control on the oxygen isotopes. Depletion in oxygen isotopes toward the ore body applies only to the dolomite, not the siderite. Siderite is enriched relative to both the outer carbonate halo and to dolomites from elsewhere in the formation.

4.4 SULPHUR ISOTOPES

The sulphur isotope stratigraphy of the Lady Loretta mine sequence has been compiled by Aheimer (1994), Carr (1981) and McGoldrick *et al.* (1995). The S isotope signature of pyrite is lightest in the Lower Carbonate Unit and increases systematically over a vertical thickness of about 180 m to the heaviest values in samples from the upper Cyclic Unit. In the Ore Sequence, base metal sulphides are isotopically heavy and indistinguishable from the stratigraphically equivalent pyrite values. McGoldrick *et al.* (1996)* interpreted these observations to suggest that the pyrite and economic mineralisation shared a common S source. The stratigraphic trend of increasingly heavy isotopes is interpreted to indicate closed-system biogenic sulphate reduction (McGoldrick *et al.*, 1996)*.

4.5 PHOSPHATE CONTENT

The P_2O_5 content of the Lady Loretta Formation warrants discussion because relatively high concentrations are commonly associated with condensed shale-prone sequences in the northern Mount Isa Basin (McConachie and Dunster, 1996)* and Bradshaw (1996b) suggested that stratiform stratabound mineralisation was found in such sequences.

Comparison of the P_2O_5 data for the Lady Loretta ore body with other pyritic carbonaceous shales in the Lady Loretta Formation and a peritidal mixed carbonate/siliciclastic sequence shows no relative enrichment in the ore or Ore Equivalent Sequence.

Location and Stratigraphy/Lithology	n	μ	Max	Min	Reference
Ore in Small Syncline, Lady Loretta	7	0.07	0.34	<0.01	Carr, 1974, 1981
Ore Sequence Equivalent, both synclines	8	0.06	0.35	<0.01	Carr, 1981
Mine stratigraphy, excl. Ore Sequence Eq.	22	0.09	0.39	<0.01	Carr, 1974, 1981
Pyritic carbonaceous shale, Johnson Ck	23	0.15	0.55	<0.01	Taylor, 1973
Pyritic carbonaceous shale, Carrier	-	0.20	-	-	Berg, 1986
Peritidal carbonate/siliciclastics, Amoco 83-5	17	0.08	0.20	<0.01	McGoldrick, 1994

Table 4-1: Percent P_2O_5 *data for the Lady Loretta Formation.*

4.6 SILICA - VARIETIES OF QUARTZ AND CHERT

The varieties of quartz minerals present in the Lady Loretta Formation have been studied in four main lithologies:

- cauliflower cherts
- silicified ooid grainstones
- silica flood and quartz veins
- surficial silcretes.

Silicification includes a variety of different varieties of quartz distinguished by their optical properties and crystal morphologies. The terminology is summarised in the Table 4-2.

Terminology	Crystal Form	Colour	Optical Properties	Habit
quartzine	fibrous, euhedral, commonly double terminated	colourless	length-slow, fibre parallel to c-axis	replacement, commonly pseudomorphing evaporite
lutecite	fibrous, pseudo-fibrous, sometimes spherulitic	colourless	length-slow, elongate areas of undulose extinction, fibre axis at 30º to c-axis	intermediate between chalcedonite and quartzine, replacement, commonly pseudomorphing evaporite
chalcedonite rinds	fibrous, concretionary rinds or overlays	conspicuous brown banding	length-fast, alternate black and white sweeping extinction, fibre parallel to c-axis or twisted helically	void-fill, also occurs in silcretes, volcanic rocks and hydrothermal deposits
spherulitic chalcedonite	fibrous, spherulitic	mostly colourless, sometimes brown banding	mostly length-fast, rarely length-slow, sometimes intergrown, pseudo-uniaxial extinction cross, helical twisting of fibre relative to c-axis	void-fill or replacement, also occurs in silcretes
megaquartz	granular, >20 μm, commonly 120º crystal junctions	mostly colourless, depending on inclusions	mostly undulose extinction	equant crystals or progressive increase in crystal-size from margin to centre, mostly void-fill, sometimes replacement
microquartz	granular, < 20 μm	mostly colourless	variable extinction, sometimes pin-point or flamboyant	void-fill, sometimes replacement

Table 4-2: Terminology used in naming varieties of quartz found in the Lady Loretta Formation. The colour refers to thin sections seen in plain polarised light. Derived from Hesse (1989), Milliken (1979) and Wilson (1966).

Cauliflower cherts form from sulphate evaporite nodules by replacement and/or void-fill by silica (see Section 11.4.5). The sulphates may be pseudomorphed by lutecite and/or quartzine, or the sulphates can be dissolved to form a void that is then infilled by chalcedonite and/or megaquartz. As discussed in Section 11.4.5, their diagenesis can be used to establish the relative timing of pyrite formation and of base metal mineralisation with respect to the different generations of quartz.

Almost all the ooid grainstones in the Lady Loretta Formation are at least partly silicified. Petrographic studies identified microquartz, megaquartz, and minor lutecite and chalcedony. Their overall diagenetic sequence is similar to that of the cauliflower cherts. Preferential silicification of the ooids affects either the nuclei, and/or discrete bands within the cortex (see Figure 6-2). The original carbonate cements are almost always silicified and it is often difficult to distinguish silica-replacement of final generation carbonate void-fills from primary megaquartz.

Pervasive silica flood of carbonates produces a so-called "silica-dolomite" texture associated with the Carlton Fault Zone about 80 m stratigraphically below the deposit. A similar texture is also present in core from drillhole CM35, again associated with a fault zone. Such "silica-dolomite" is the host of much of the Cu mineralisation at Mount Isa and both the afore-mentioned occurrences in the Lady Loretta Formation contain anomalous levels of Cu. However, in contrast to the situation at Mount Isa, the silica flood in the Lady Loretta Formation clearly postdates both the formation of some euhedral pyrite and the stylolitisation of the host carbonates and can be interpreted to indicate that any associated Cu mineralisation is epigenetic.

The "silica-dolomites" and many other faulted intersections and exposures of the Lady Loretta Formation contain numerous quartz veins. The veins range in size from internally fibrous veinlets a few millimetres wide to pods such as associated with the Western Border Fault and other major faults. Such "quartz blows" are visible on airphotos. Much of the Ore Sequence and Cyclic Unit at the Lady Loretta mine contain distinctive coarsely-fibrous crack-seal quartz veins comprised of one or more generations of translucent to white silica arranged at right angles to the wall of the vein. All these occurrences of veins almost certainly formed synchronous with one or more major tectonic episodes. It is noteworthy that the fibrous veins from the mine pre-date the folding that produced the synclines. Personal observation and geochemical assays in company reports suggest that the vein-silica hosts considerable pyrite locally (*e.g.* Brenda Creek area) and some occurrences are anomalous in Cu (Kamarga Dome). However, there is no evidence of associated Zn or Pb away from the mine.

Petrographic study of the silica in surficial silcretes (Chapter 12) show a complex history of silica precipitation and dissolution. Unusual quartz cements, usually found only in combination in silcretes, include length-fast chalcedony and intimate mixtures of length-slow and length-fast quartz and checkerboard chalcedony. Much of the chalcedony occurs as void-fill spherulites with pseudo-uniaxial extinction crosses.

4.7 MICAS AND CLAYS

Both detrital and metamorphic muscovite and chlorite have been identified in the Lady Loretta Formation.

The distribution and abundance of detrital mica in the Lady Loretta Formation (Figure 4-1) may give some indication of the changes to provenance. Siltstone and fine grained sandstone containing a particularly high concentration of detrital mica were noted at approximately the same lithostratigraphic level in the lower third of the Lady Loretta Formation at Thornton River and Russell Creek B sections. A highly micaceous red-bed siltstone that can be traced for several hundred metres along strike occurs in approximately the same lithostratigraphic level at Trent.

This may be interpreted to suggest a local change in provenance in that area and a possible granitic or metamorphic source terrain. There is no evidence of widespread mica-rich beds in the Kamarga Dome region. Thus, the metamorphics, granite and volcanics that are the core of the present dome were unlikely to have been exposed during the deposition of the Lady Loretta Formation.

Outcrop of a thin micaceous sandstone bed in the Upper Clastic Unit in the Big Syncline cannot be correlated to nearby drillhole intersections or to the litho-stratigraphically equivalent unit in the Tom Cat area and appears to be of only local significance.

Metamorphic muscovite and chlorite were identified in the host rocks to the Lady Loretta ore body and cited as evidence of lower greenschist metamorphism by Carr (1981) and Etheridge and Lee (1975) (see Section 11.7).

The most abundant clays in the Lady Loretta Formation are illite and kaolinite. Carr (quoted in Lemcke, 1986) noted that the kaolinite found in and near the Ore Sequence at the Lady Loretta mine gave a different X ray diffraction pattern to kaolinite form the weathered Ore Sequence equivalent.

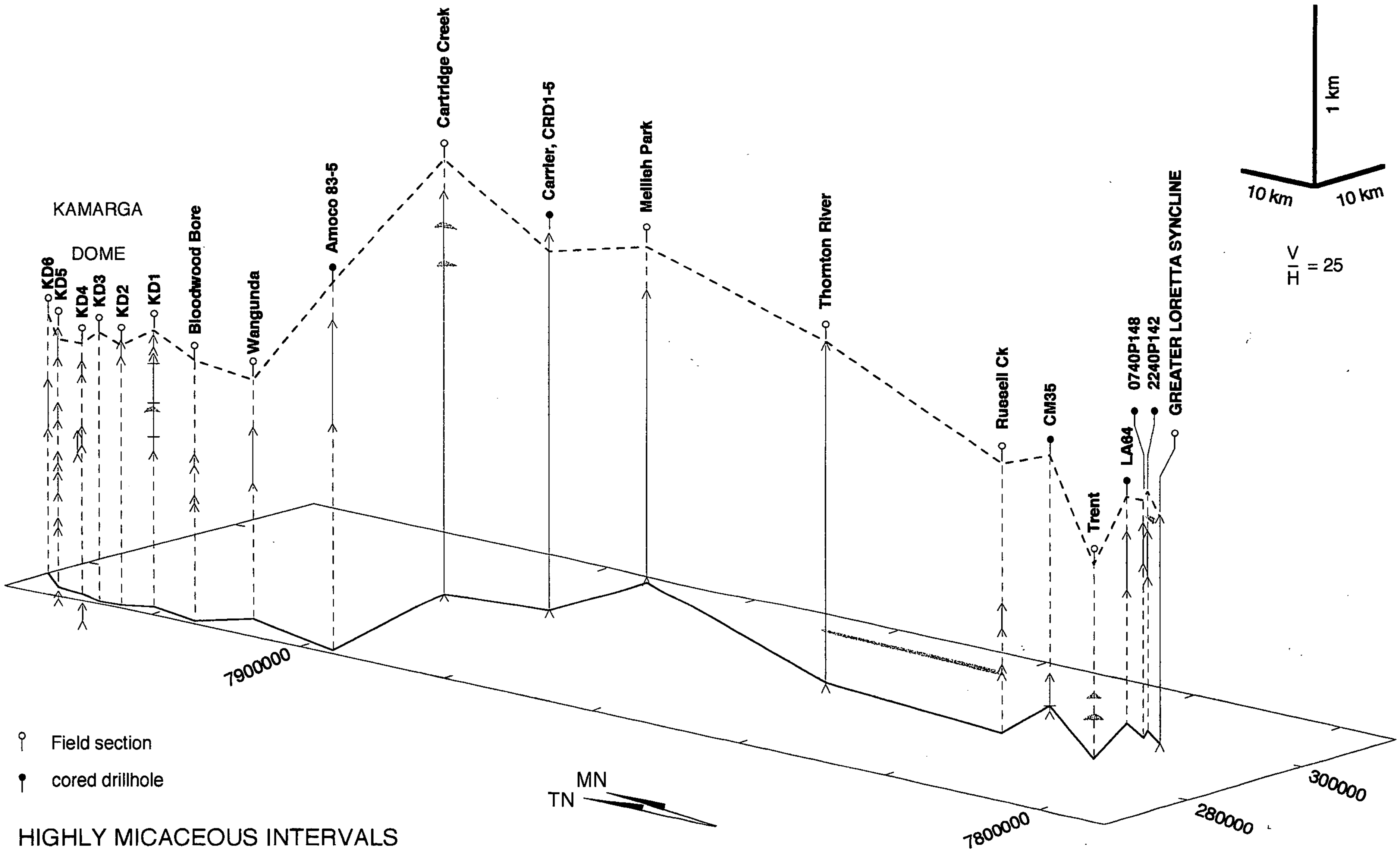
A pilot study of the illite crystallinity was in progress at the time of writing (McGoldrick, in prep.), but results have not been interpreted.

4.8 CARBONACEOUS MATTER

The Lady Loretta Formation contains numerous highly carbonaceous facies that occur at various levels in the lithostratigraphy. Some extend for several kilometres and others are localised. Not all carbonaceous facies are consistently pyritic. Since the carbonaceous lithologies are deeply weathered in outcrop, the only reliable analyses come from core and RAB holes.

Carbonaceous matter is a conspicuous component of the ore in all north Australian SSHBM ore bodies, including Lady Loretta, and the presence of high concentrations of organic carbon is an important element of some genetic and exploration models.

Figure 4-1: Distribution of highly micaceous lithologies in the Lady Loretta Formation.



HIGHLY MICACEOUS INTERVALS

Background to the types and study of organic matter in the Proterozoic rocks of northern Australia is given in Crick (1989 *et seq.*), Glikson (1990) and Glikson *et al.* (1989, 1992).

Dorrins *et al.* (1983) undertook TOC analyses of core from the Lady Loretta Formation in drillhole Amoco 83-5. Values ranged from less than 0.01 to 0.26 wt%, averaging 0.09% TOC. This core contains relatively little pyrite and no base metal mineralisation. The TOC and Fe content of the more argillaceous samples have a low statistical correlation coefficient ($r^2 = 0.2$).

A suite of 20 samples from a variety of lithologies in the Johnson Creek area was analysed by Taylor (1973). Values (μ = 1.1 wt%, σ = 4.5 wt%) are biased by one extremely high result of 20.08 wt% TOC. This anomalous value cannot be explained by the presence of siderite (see Appendix A-6.2) and may be interpreted to indicate the presence of bitumen. When this single value is excluded, the statistics are: max = 0.55 wt%, μ = 0.13 wt%, σ = 0.16 wt%. There is a positive relationship ($r^2 = 0.8$) between TOC and Fe content in shales.

Analyses of ten RAB samples from moderately weathered black shales from the lower Lady Loretta Formation in the Redie Creek area ranged between 0.03 and 3.4 wt% (μ = 0.15 wt%) TOC and six shale samples from the Trent area averaged 0.18 wt% with a similar range (unpublished CEC data from files held at Lady Loretta mine).

Studies of organic matter have been undertaken in the vicinity of the Lady Loretta ore body by Carr (1981), Crick (1997) and as part of the present study. The method of TOC analysis is described in Appendix A-6.2 and the level of maturity of the organic matter is discussed in Section 11.2.2. Determinations of TOC are complicated by the presence of siderite (as discussed in Appendix A-6.2) and bitumen (as described below).

Initial work by Carr (1981) indicated that there was a positive correlation between pyrite and TOC contents at the Lady Loretta mine, but he did not specify if this applied only to specific generation(s) of pyrite. Carr (1981) cites 0.1 wt% TOC in dolostones and sideritic dolostones, ranging up to about 0.9 wt% in dark silty shales. Highly pyritic rocks contain up to about 8 wt% TOC as reported from the Pyritic Unit / Ore Sequence contact in drillhole 2480P128 (Carr, 1974). During the present study, the TOC content of 13 siderite-free samples from a wide range of lithologies within 12 m stratigraphically of the top of the Ore Sequence were determined (see Appendix A-7). The maximum of 2.1 wt% (μ = 0.8 wt%, σ = 0.56 wt%) is lower than Carr's (1981) analyses. It is now suspected that some of the highest TOCs obtained by Carr (1981) may have come from below the Carlton Fault (and not be Lady Loretta Formation) and that his results are biased by the inclusion of samples that contain high levels of migra-bitumen (see below), diagenetic concentration in layers of pressure dissolution or graphitic zones associated with small scale shearing. It is also unclear if his analytical technique allowed for siderite contamination.

Comparison of the recent analyses from the vicinity of the mine with the scant available data from shales elsewhere in the Lady Loretta Formation indicates that, on average, the host rocks are significantly higher in TOC, but that similar maximum values probably exist elsewhere in the formation. Furthermore, the mean of 0.8 wt% from the host rocks is above the 0.67% average TOC content for carbonate rocks worldwide (Tissot and Welte, 1978). Organic-rich rocks known to have generated petroleum had original TOC contents as low as 0.3 to 0.5 wt% (Palacas, 1983). Thus, given the thermal maturity of the Lady Loretta Formation generally, and the host rocks in particular (see Section 11.2.2), the TOC-rich shales will have undoubtedly sourced hydrocarbons.

Indeed, Carr (1981) recognised widespread bitumen in most samples from the vicinity of the Lady Loretta ore body. Bitumen is also common in other SSHBM ore bodies. It can form in two ways. Usually, it is a product of normal thermal maturity and may be *in situ* or migra-bitumen. In the case of the Lady Loretta mine samples (and others from the Mount Isa Basin studied by Crick, 1997), a significant proportion of the bitumen formed as thucholite. This is the product of polymerisation of hydrocarbons around a radioactive mineral and commonly produces higher reflectances than thermally-matured bitumen in the same sample (see Section 11.2.2). In samples with max Ro of about 2.5%, the thucholitic bitumen has been mobilised and dispersed (Crick, 1997).

Analyses of bitumen from the Ore Sequence detected anomalously high concentrations of Fe, Cu, Ni and Zn (Carr, 1981). Neither Cu nor Ni were detected in pyrite in the bitumen. Lemcke (1986) interpreted Carr's (1981) description of these relationships to suggest that mineralisation post-dated the generation and migration of oil. However, the complications of multiple sources of bitumen, evidence of at least two migration events and the possible tectonic remobilisation of some metals, preclude such a simplistic interpretation.

4.9 ORE TEXTURES AND MINERALOGY

The minerals present in the ore body are (in approximate order of decreasing abundance): pyrite, quartz, sphalerite, galena, barite, siderite, dolomite, carbonaceous matter, K feldspar, muscovite and other phyllosilicates, chalcopyrite, haematite, tetrahedrite-freibergite, marcasite, arsenopyrite, pyrrhotite and zincian greenockite [(Cd,Zn)S] (Carr, 1981; McGoldrick *et al.*, 1995; Paterson, 1985). Aheimer (1994) reported an unusual low-K stilpnomelane intergrown with early sphalerite. In addition, kaolinite and secondary goethite are present in rocks that have been altered by acid groundwaters (Carr, 1981). Rare Zn and Pb carbonates have been reported associated with the "gossanous" surface expression of the Ore Sequence.

The ore textures have been described in detail by Aheimer (1994), Carr (1981) and McGoldrick *et al.* (1995). Aheimer (1994) recognised nine textural subdivisions and Carr (1981) four. The following is a precis of their observations for specific ore minerals, augmented by the author's observations.

Pyrite is by far the most abundant sulphide in the vicinity of the Lady Loretta mine and Carr (1981) recognised several types:

- a euhedral, etch-resistant form comprising individual grains of a few microns in size or aggregates of these grains
- easily-etched, subhedral pyrite that overgrows the above
- a much coarser (10s to 100s µm) euhedral variety, some of which is the distinctive porous "reactive" pyrite (see photograph in Appendix A-3)
- a rare tabular to prismatic variety occurring as single grains a few tens of microns long or as clusters of grains within a sphalerite matrix.

The first two types are the dominant constituent of the laminated pyrite throughout the sequence from the Pyritic Unit to the Cyclic Unit, including the Ore Sequence. The coarser pyrite is commonest in, and immediately underlying, the ore beds.

Sphalerite is the main economic sulphide in the ore and two distinct varieties are present:

- abundant dark brown to deep orange, coarse grains (typically 100-300 µm, but up to a millimetre) with abundant inclusions of both coarse and fine grained pyrite, chalcopyrite and carbonaceous matter
- rare pale yellow finely intergrown crystals (5-50 µm across) sometimes paragenetically earlier than the variety described above.

The majority of the galena has irregular grain boundaries and occurs interstitial to other sulphides. Thin, almost pure galena layers occur interbedded with mixed sulphides and as partial replacements of carbonaceous laminae in microbialites. Galena commonly occurs as fracture-fill and is tectonically remobilised into tension gashes and as the matrix of breccias. McGoldrick *et al.* (1995) reported an unusual association of spherical galena and marcasite.

Tetrahedrite-freibergite has been recognised as a minor phase occurring as anhedral crystals adjacent to, or within, galena grains or as narrow veinlets. Analyses by Carr (1981) showed a wide diversity in chemical composition depending on Ag-Cu and Zn-Fe substitution. Comparison with tetrahedrite-freibergite from Mount Isa shows that the Lady Loretta samples are consistently higher in Cu and Zn (Carr, 1981).

4.10 OTHER ELEMENTS ASSOCIATED WITH MINERALISATION

4.10.1 Introduction

The distribution and concentration of individual elements in selected lithologies in the Lady Loretta Formation have been the subject of several previous studies. Such studies hoped to identify potential pathfinder elements for SSHBM mineralisation or to infer the source of metals or the source of the brines responsible for metal transport.

Two major geochemical studies designed to evaluate potential pathfinder elements have been undertaken in the vicinity of the Lady Loretta mine. The West German Federal Institute of Geoscience and Natural Resources conducted multi-element analyses of 193 gossan and rock chip samples from outcrop in both synclines. That study identified Zr, Y, Th, Ni, K and Hg as potential pathfinders to Zn-Pb-Ag mineralisation at

Lady Loretta mine (Lemcke, 1986). CODES AMIRA/ARC Project P384 identified Tl and Mn in dolomite as other potential indicators and went on to develop a suite of indices based on comprehensive multi-element analyses of core (Large and McGoldrick, 1993; McGoldrick, 1993). The following discussion concentrates on individual elements and, unlike previous studies of the ore body geochemistry, compares concentrations to similar lithological facies elsewhere in the formation. As such, it forms part of the recommended exploration program discussed in Chapter 14.

4.10.2 Barium

The highest barium levels in the Lady Loretta Formation are associated with barite. Bedded barite is known only from the Lady Loretta mine, but locally significant barite does occur elsewhere in the formation. These occurrences include barite in cores of cauliflower cherts in the northern Lady Loretta Formation, as the matrix to an intraformational breccia on the flanks of Kamarga Dome (Pringle and David, 1983) and as a barite blow associated with the Termite Range Fault (7879400N 293800E). The latter occurrence is associated with a small Cu prospect.

"Background" Ba values for the Lady Loretta Formation reported by McGoldrick (1994) range from 15 ppm to 3380 ppm. The higher of these concentrations are associated with millimetre-scale barite pseudomorphs of sulphate evaporites in core from Amoco 83-5. Other Ba analyses away from the Lady Loretta mine are from the Carrier area (Berg, 1986). There, Ba levels were reported as locally anomalous in pyritic facies in drillholes CRD3 and CRD5. Representative compositions given by Berg (1986) are summarised below. The only detailed analyses presented are from carbonates. They contain up to 502 ppm Ba (μ = 207 ppm) but there does not appear to be any positive statistical correlation with metals in the carbonates (see Appendix A-8).

Drillhole	Lithology	Ba (ppm)
CRD1	pyritic carbonaceous siltstone	430
CRD2	graded sandstone	350
CRD4	carbonaceous siltstone	380
CRD5	"tuffaceous" silicified siltstone	530
CRD5	dolomite breccia	440

Table 4-3: Representative Ba concentrations in core from the Carrier area. The data are summarised from Berg (1986).

Recognition of the intimate association between barite and ore, both in the gossan and in underground ore at Lady Loretta, led to early attempts to use Ba as a pathfinder element. Initial work was encouraging, with a 1975 rock chip sampling program demonstrating a good correlation of Ba with Ag and Zn (Russell *et al.*, 1976) and analyses of core by Carr (1981) clearly demonstrated that the highest Ba levels were in the immediate footwall. Unpublished data on whole rock analyses of core gathered by McGoldrick also show a correlation between Ba and Zn (McGoldrick *et al.*, 1995). The application of Ba as a pathfinder element was further tested by stream sediment and soil sampling at the Lady Loretta mine, but this showed no clear relationship to the mineralisation (Lemcke, 1986).

The relationships between barite, pyrite and Zn-Pb-Ag mineralisation have been examined in detail. The Ba content of pyrite was analysed systematically throughout the stratigraphy by McGoldrick *et al.* (1995) who concluded that the pyrite was not anomalous in Ba and that no systematic variation exists with respect to stratigraphic position. Re-examination of these analyses suggests that this may be a simplification since the highest absolute Ba concentrations do occur in, or within 10 m of, the Ore Sequence. Nor do these analyses differentiate between different generations of pyrite that may have either preceded, been synchronous with, or post-date mineralisation. Further work would be needed to sustain the original interpretation that, since the Ba concentration in pyrite did not vary systematically with respect to the Ore Sequence, the "pyrite [and, by inference, the barite] and base metal sulphides are not directly related" (McGoldrick *et al.*, 1995).

Fluid modeling by Cooke (1993a *et seq.*) indicated that barite is unlikely to have been carried by the same fluid that introduced the base metals.

In summary, the presence of barite in outcrop should not be ignored in the search for Lady Loretta-style ore bodies but barite content will not be of much use in stream sediment or soil samples. Although the barite is unlikely to have been introduced with the base metals, this has yet to be convincingly demonstrated and its relationship to the environment of deposition of the host sedimentary rocks may yet prove to be important. The origin of the barite is discussed in Section 13.4.9.

4.10.3 Cadmium

Cadmium is a good indicator element for sphalerite and chalcopyrite mineralisation. Since Cd substitutes for Zn, the ratio of Zn/Cd remains constant at about 500 in most geological situations. Cadmium is an industrial metal in its own right and is a by-product of the refining of Mount Isa Pb-Zn-Ag ore.

Carr (1981) noted a strong association between Cd and Zn in a variety of lithologies from the vicinity of the Lady Loretta mine. The 270-360 ppm class interval of the Cd distribution corresponds to the 17-34% modal class interval of the Zn distribution (Carr, 1984). Carr (1981, 1984) did not present his raw data for Cd analyses and so variation from the theoretical Zn/Cd of 500 cannot be assessed. However, an earlier study (Carr, 1974) lists correlation coefficients for Zn and Cd in the Small Syncline on a drillhole by drillhole basis (average $r^2 = 0.917$, n = 23 drillholes). This study showed a consistently good correlation between the two elements and described a vertical variation related to distance from ore with the best correlations and highest absolute Cd values coming from the laminated ore, as opposed to tectonically remobilised ore. Varieties of sphalerite high in Cd are commonly brown or yellow but there does not appear to be such a simple relationship at Lady Loretta.

Paterson (1985) reported zincian greenockite (primary cadmium sulphide) associated with sphalerite over a *ca.* 15 m interval in the Ore Sequence in drillhole 2420P166.

Cadmium analyses of core of the lower Lady Loretta Formation in the Johnson Creek area were all below the 10 ppm level of detection (Taylor, 1973).

There are no published data for Cd distribution in soil or stream sediments around Lady Loretta, but it would be expected that any anomalous Cd would also be accompanied by measurable Zn. The strong association between Cd and Zn in a variety of different geological environments means that both elements were probably introduced together during mineralisation.

4.10.4 Mercury

Mercury is generally regarded as a mobile pathfinder element to base metal mineralisation and much of the early interest in the geochemistry of the Lady Loretta ore body was related to Hg (Russell *et al.*, 1976; Lemcke, 1986). Carr (1981) demonstrated that unmineralised pyritic layers from Lower Carbonate Unit in the Small Syncline (underlying ore) contained between 500 ppb and 53 ppm Hg. This anomaly extends for up to 40 m around the ore body (Carr, 1984). In contrast, pyrite in the same stratigraphic interval in the Big Syncline (lacking economic mineralisation), is generally less than 700 ppb. Programmed pyrolysis indicated that the Hg occurs within the pyrite structure and chemisorbed onto pyrite surfaces (Carr, 1981).

Subsequent analyses demonstrated that fresh ore, itself, contains an average of 21 ppm Hg. This is mostly associated with sphalerite, although minor amounts also occur in tetrahedrite or pyrite inclusions (Carr, 1984; Lemcke, 1986). There is a good correlation between Zn and Hg throughout the Ore Sequence (Carr, 1984). Carr (1981, 1984) reasoned that Hg was introduced with the mineralising fluid and, contrary to the general opinion at the time, that its distribution was unaffected by greenschist facies metamorphism.

Ground and airborne Hg surveys reported in Lemcke (1986) detected surface anomalies associated with the western limb of the Small Syncline and several of the major faults that penetrate ore.

In contrast to the Ore Sequence, Hg values in the pyritic facies intersected in drillholes CRD1-5 in the Carrier area all have <0.05 ppm Hg. This can be interpreted to suggest that Hg might be a useful indicator of Zn mineralisation in the Lady Loretta Formation.

4.10.5 Thallium

The Lady Loretta ore body has a pronounced Tl halo with elevated values occurring for more than 100 m around the ore (McGoldrick *et al.*, 1995) and a similar halo exists around the Mount Isa ore body. At Lady Loretta, values increase from <4 ppm in the outermost dolomite to >50 ppm in the inner siderite zone and ore (Figure 1 in Large, 1994). The thallium content of pyrite also varies systematically with respect to the ore position. Absolute values in the Ore Sequence range up to 376 ppm, which is ten times the concentration in the outer halo. When recalculated to 100% pyrite, the pyrite in the Ore Sequence is enriched in Tl up to three times background (data in McGoldrick *et al.*, 1995).

Background Tl concentrations from Amoco 83-5 are consistently at, or below, the 1 ppm limit of detection (McGoldrick, 1994). All the lithologies analysed in the Carrier area, including highly pyritic facies, contain <10 ppm Tl (Berg, 1986). On the basis of these data from the Lady Loretta Formation, Tl appears to be a reliable indicator of base metal mineralisation and the implication is that Tl was introduced with the Zn-Pb-Ag.

4.11 SUMMARY

The present study has demonstrated significant characteristics and associations of the carbonate mineralogy and geochemistry of the Lady Loretta Formation. The original shallow marine carbonate was probably not aragonite. Sulphur isotopic studies can be used to argue for restricted circulation in the water body in the vicinity of the mine. Iron-rich, magnesian and manganiferous carbonates appear to be commonly associated with highly pyritic and carbonaceous (average *ca.* 0.1 wt% TOC) lithologies and are not restricted to the halo around the mine. However, the halo is significantly enriched in Cd, Hg and Tl relative to similar lithofacies elsewhere. There is a systematic, mineral specific, variation in the oxygen isotopic composition of the carbonates in the halo at the Lady Loretta ore body. The Lady Loretta Formation has a complex history of silicification, at least some of which postdates diagenetic pyrite but pre-dates epigenetic base metal mineralisation.

Chapter 5 - Evidence of Fluctuating Tidal Activity and Intermittently Very Shallow Conditions

5. EVIDENCE OF FLUCTUATING TIDAL ACTIVITY AND INTERMITTENTLY VERY SHALLOW CONDITIONS

5.1 INTRODUCTION

Studies of modern tidal deposits have led to the recognition of several diagnostic sedimentary features that are also found in ancient analogues (see reviews in Flemming and Bartholoma, 1995). Tidal bedding can take many forms: flaser, lensoidal to lenticular bedding, compound and herringbone crossbedding and rhythmically bedded laminated sequences. Several of these were recognised in the Lady Loretta Formation by previous workers (*e.g.* Sweet and Hutton, 1982). Other diagnostic tidal features recognised in the Lady Loretta Formation include reactivation surfaces associated with herringbone crossbeds and bimodal/bipolar palaeocurrent trends (Dunster, 1996*).

The Lady Loretta Formation also contains a suite of sedimentary structures indicative of shallowing-up to near emergence. Diagnostic ripple morphologies and modifications to ripple crests are very common. Wash-out rills, scour pits, millimetre ripples, wrinklemarks and possible microkarst have also been reported. These are augmented by shrinkage cracks including good examples of both desiccation and synaeresis cracks.

5.2 FLASER- TO LENTICULAR-BEDDED UNITS

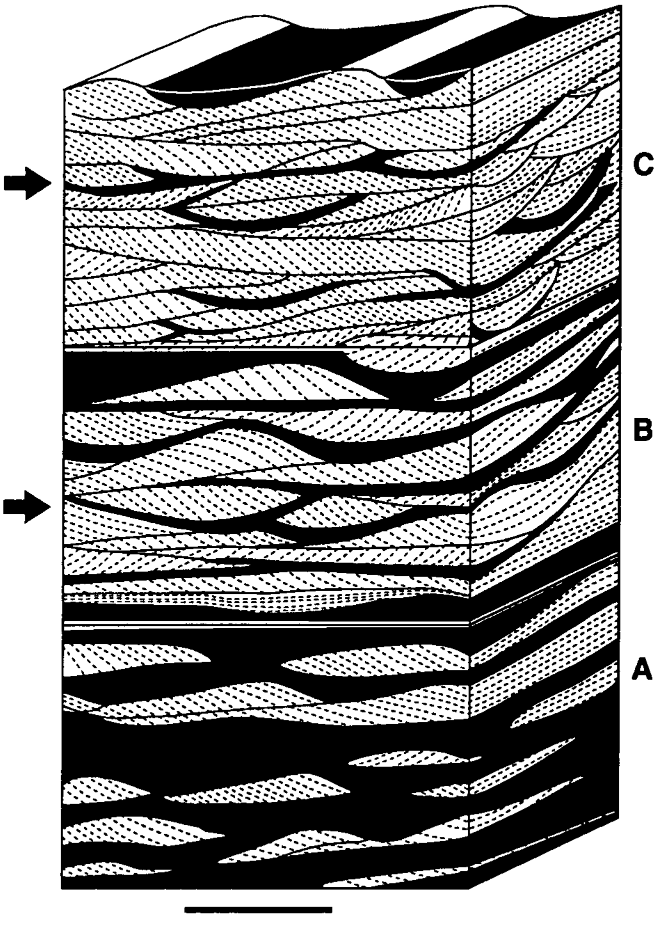
5.2.1 Description from Literature

Heterolithic interbedding of sandstone and claystone or carbonate occurs at various scales and has been described using several different classification schemes. Reineck (1960) and Reineck and Singh (1980) recognised a spectrum of flaser, wavy and lenticular tidal bedding as shown in Figure 5-1. Their original definitions were partly based on ripple geometry and have been broadened by subsequent workers. Demicco and Hardie (1994) stressed that it is still necessary to examine examples in three dimensions before they can be classified under this scheme.

Flaser bedding occurs in sand-dominated rocks or where sand and finer fractions are in approximately equal amounts. The flasers are clay or carbonate mud drapes and must be lensoidal in three dimensions.

As originally defined, wavy bedding was restricted to clay layers that are draped continuously over both asymmetrical and symmetrical ripples. Bifurcating flasers, as defined by Klein (1977), occur in both flaser and wavy bedding (Figure 5-1). Lenticular tidal bedding occurs in rocks with a high mud to sand ratio, where current ripples are preserved as lenticular beds. Some of the lenticular beds have internal flaser bedding. Demicco and Hardie (1994), amongst others, extended the definition of wavy bedding to include the "ribbon rock" of other authors. This includes near-parallel lamination within the spectrum of tidal bedding.

Figure 5-1: A schematic representation of tidal bedding. A at the base represents lenticular bedding, B is wavy tidal bedding and C is flaser bedding. Bifurcating flasers are shown at the levels of the arrows. The progression from A to C corresponds to a net increase in current speed, decreasing deposition and decreasing preservation of mud drapes (after Reineck and Singh, 1980). The bar scale is 1 cm.


C
B
A

5.2.2 Examples from Lady Loretta Formation

Outcrops of both the Esperanza Formation and the Lady Loretta Formation contain good examples of flaser, lenticular and wavy bedding. Figures 5-2d,e show a number of different examples from the Lady Loretta Formation. Such facies were recognised from almost all measured sections including beneath the Ore Sequence at Lady Loretta mine. All three types of bedding commonly occur together and grade from one to another. The lithologies range from almost entirely clastic to mixed carbonate/siliciclastic. Figure 5-2e illustrates an example of flaser to lenticular bedding from Kamarga Dome.

Flaser bedding is common in mixed carbonate/siliciclastic lithologies in the Brenda Creek area where both single and bifurcating flasers were identified in outcrop. Similar, although smaller-scale, features occur in core from the nearby drillhole Amoco 83-5.

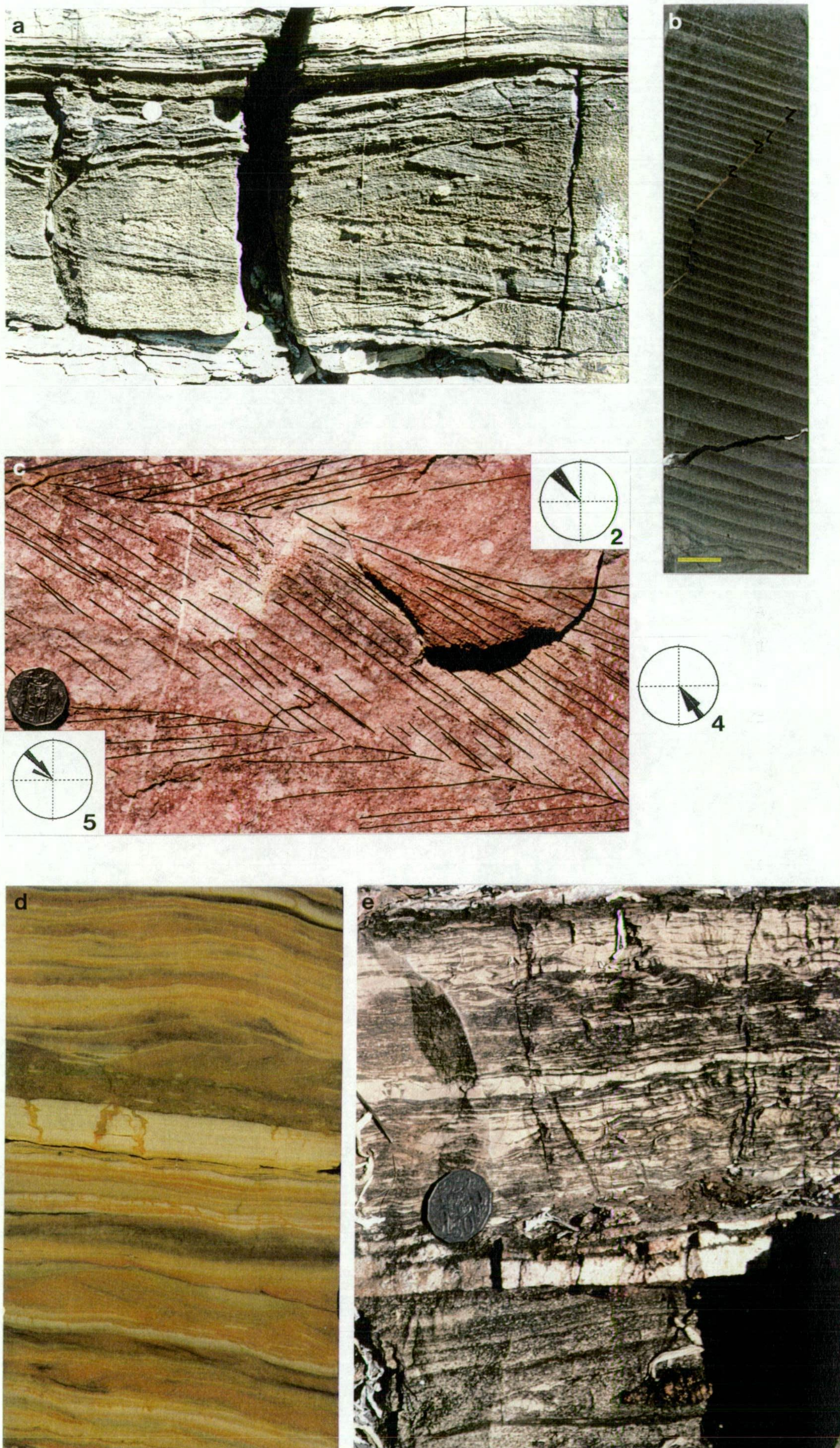
Rare outcrop of the Lady Loretta Formation from beneath the mine sequence adjacent to Western Border Fault contains wavy and lenticular bedding in fine to medium grained sandstone and slightly dolomitic claystone (*e.g.* sample L3C213). Ripples from this area contain bundled chevron-upbuilding and are associated with flaser-like clay drapes (see Appendix A-11).

5.2.3 Interpretation

Studies of modern tidal flats have demonstrated that this complex spectrum of bedforms, as observed in the Lady Loretta Formation, results from the interplay of a regular alternation between bedload and suspension affecting sediments of different compositions. Bedload processes transport the sand-size fraction and settling from suspension gives rise to thin layers or flasers of clay-sized particles or carbonates (Klein, 1977). This equates to the flow and ebb of the tide.

In ancient examples, flaser bedding is interpreted as part of a continuum of wave-generated structures typical of a tidal environment (de Raaf *et al.* 1977; Reineck and Singh, 1972). In the original interpretations by de Raaf *et al.* (1977) and Reineck and Singh (1972), the different forms were believed to be controlled by the relative volumes of sand and mud, the relative duration of both the bedload and suspension mode of deposition, and by flow velocities. If sand exceeds mud, ripples form with isolated clay drapes. If mud and sand content is nearly equal, flaser bedding is produced. With a high mud to sand ratio, current ripples are preserved as lenticular beds. Wavy bedding forms when clay layers are draped continuously over both asymmetrical and symmetrical ripples (de Raaf *et al.*, 1977; Klein, 1985). However, it has been argued that a single slack water period in a tidal cycle could not suspend sufficient clay to produce the individual flasers of up to 1 cm thick and that such uncompacted flasers would be eroded by the next tidal cycle. This was partly refuted by the field experiments by Reineck and Wunderlich (1968) who used different coloured dye markers to record deposition during each incoming and outgoing tide over a number of cycles and showed that the finer-grained fractions were

Figure 5-2: (a) Trough crossbedding in a granule conglomerate at Kamarga Dome. This unit occurs between mixed carbonate / siliciclastics. (b) Rhythmites with a non-random arrangement of thicknesses, 2420ED62, 41m. (c) Herringbone crossbedding with 180° opposed palaeocurrent directions, Gundaria Bore. The numerals refer to the number of measurements taken along strike. (d) Stacked couplets with opposed ripple crosslamination, Amoco 83-5, 536.1 m. (e) A classic example of tidal bedding. Ooid grainstone overlain by the full spectrum of lenticular→wavy tidal→flaser bedding. In this example the dark material is the coarser- grained fraction making this photo a negative image of the theoretical spectrum of tidal bedding illustrated in Figure 5-1. Coin is 3 cm d and bar scale is 1 cm.


a
b
c
2
4
5
d
e

being preserved. The explanation favoured by Demicco and Hardie (1994) that relies on the peloidal (and therefore easily compacted) nature of the slack water fines has application to the modern North Sea tidal flats were the majority of such sediment consists of faecal pellets, but is probably not applicable to the Palaeoproterozoic.

Collectively, flaser- to lenticular-bedded units are typical of tidal flats (Allen, 1985) but isolated examples also form in subtidal areas as a result of storms (McCave, 1970) (see Section 7.1). Dalrymple (1992) described the continuum from flaser bedding in low intertidal mixed sand/mudflats to wavy bedding and lenticular bedding on the high intertidal to supratidal flats. A similar interpretation of mixed carbonate/siliciclastic facies by Demicco (1983) attributed wavy and lenticular bedding to a shallow subtidal to intertidal setting where they constituted the regressive deposits of carbonate tidal flats.

Examples from the Lady Loretta Formation have been interpreted similarly with sequences with abundant flaser bedding assigned to the lower intertidal zone and those with most abundant lenticular bedding assigned to the upper intertidal zone.

5.3 DIAGNOSTIC CROSSBEDDED UNITS

5.3.1 Herringbone Cross-Stratification

Description from Literature

True herringbone cross-stratification is preserved in vertically stacked opposite-dipping crossbed sets and appears to be confined to relatively coarse grained sandstones. The set boundaries are usually very sharp and commonly associated with reactivation surfaces (see next Section). It is mandatory that both sets of cross-strata are characterised by maximum dip angles oriented 180°±10° apart (bipolar). Herringbone cross-stratification is most easily recognised in planar tabular crossbedding. In limited outcrops of trough crossbedding, care must be taken to avoid misinterpreting a partial end-on view of troughs (Dalrymple, 1992).

Examples from the Lady Loretta Formation

Herringbone cross-stratification is rare in the Lady Loretta Formation. Most examples observed during the current study were in medium to coarse grained sandstones in the transition zone between the Lady Loretta Formation and Shady Bore Quartzite. Bipolar palaeocurrent directions could only be quantified in exceptional cases where jointing permitted a three dimensional analysis (Figure 5-2c). Most examples are associated with reactivation surfaces.

Interpretation

Herringbone cross-stratification is widely used as an indication of tidal deposition. Studies of modern examples have demonstrated that it forms in response to twice daily reversing flow with each cross-strata set produced by dune or sandwave migration through a single reversed part of a tidal cycle. However, bipolar crossbedding is not universally developed in tidal sands because either ebb or flood may dominate producing a unidirectional flow pattern.

Allen (1977) and Klein (1985) illustrated excellent examples of herringbone cross-stratification from the Cambrian and Proterozoic and it has been identified in Archaean sandstones. Such clear evidence of equal ebb and flow of tides in ancient rocks has implications for the global dynamics discussed in Chapter 2.

The examples from the Lady Loretta Formation are clear evidence of tidal deposition.

5.3.2 Reactivation Surfaces

Description from Literature

Reactivation surfaces are truncation surfaces that intersect cross-stratification yet dip in the same general direction at a lower dip angle. They are commonest in coarser-grained clastic facies but do occur in silty carbonates. Klein (1985) and Nio and Yang (1991) described reactivation surfaces from modern and Holocene settings. Allen (1977) and Klein (1985) illustrated examples including Proterozoic sandstones.

Examples from the Lady Loretta Formation

Figure 5-3 is a tracing from field photographs that shows typical reactivation surfaces in a crossbedded sandstone from the Lady Loretta Formation/Shady Bore Quartzite transition at Gundaria Bore. Smaller-scale examples were noted in fine grained to silty carbonates higher in the stratigraphy at this location and from other measured sections. The most obvious reactivation surfaces occur in association with either herringbone cross-stratification or rhythmically bedded tidal bundles in forests as described in Section 5.4.

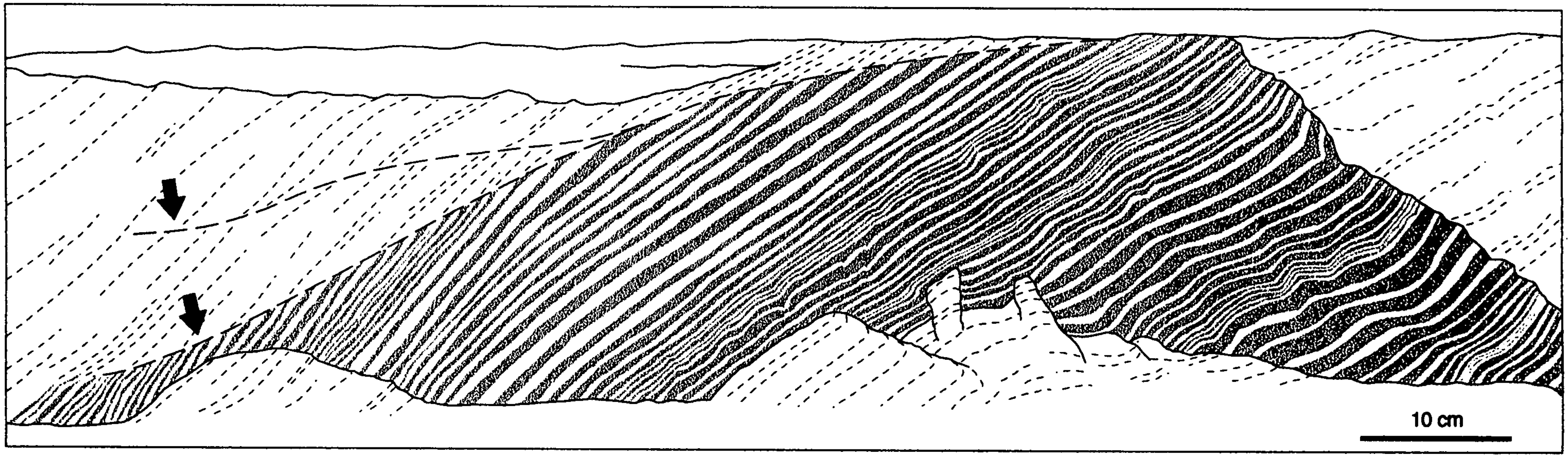
Interpretation

Reactivation surfaces are produced by the asymmetry of tidal currents. The dominant current deposits the bed and the truncation surface forms during a destructive phase coincident with the lower velocity, or subordinate, phase of a tidal cycle. Reactivation surfaces will only be preserved where bedforms are migrating, consequently the direction in ancient examples should show the direction of the dominant tidal phase and be parallel to sand body trend and depositional strike (Allen, 1977; Klein, 1985).

Reactivation surfaces have been documented from modern tidal settings and are common to many ancient tidalites. However, care must be taken in interpreting reactivation surfaces as sole indicators of tidal deposition as they are also known to occur in fluvial sediments, especially in estuarine settings where wave directions oppose fluvial flow. Reactivation surfaces have also been produced experimentally with only unidirectional flow intended to simulate a delta (Allen, 1977; Klein, 1985).

Reactivation surfaces from the Lady Loretta Formation that are associated with herringbone cross-stratification or tidal bundles are clear evidence of tidal deposition. The consistent dip direction of other examples (admittedly over a small portion of the formation) can be interpreted to suggest that the dominant tide was towards the north to northwest. It is important to note, however, that either the ebb or flood tide can dominate in different settings so this is not necessarily a vector towards shore.

Figure 5-3: Reactivation surfaces (shown by arrows) and non-random coset thickness variation in a crossbedded sequence from the Lady Loretta Formation to Shady Bore Quartzite transition at Gundaria Bore. The right-hand portion of the shaded section was used in spectral analysis. Darker beds represent finer grained units. The drawing is a tracing from a mosaic of photographs and the bar scale is 10 cm.


10 cm

5.3.3 Cross-Stratal Geometry

Studies of the internal geometry of cross-strata in modern tidal environments has led to the recognition of a suite of diagnostic features such as non-random arrangements of foreset thickness and the statistical distributions of foreset dip angle.

Crossbed Dip Angle

In areas of marked tidal asymmetry, the statistical distribution of tidal crossbed dip angles is typically bimodal (Allen, 1977). This can be demonstrated in several locations in the Lady Loretta Formation including a medium grained crossbedded sandstone from the transition to Shady Bore Quartzite at Gundaria Bore (Figure 5-4).

Set Thickness

The coset thicknesses in tidal crossbeds is commonly multi- or bimodally distributed (Allen, 1977) depending on the time-velocity asymmetry of the tides. In the Lady Loretta Formation, this is not always true of crossbeds interpreted to be of tidal origin on the basis of reactivation surfaces, bimodal dip angles and non-random arrangements of thicknesses. However, the thicknesses of cosets in at least one example of finer-grained silty carbonates from KD1A is convincingly bimodal (Figure 5-5).

A more equivocal approach is to document the non-random arrangement of foreset thicknesses (tidal bundles). As described in the following section and Appendix A-10.4, this technique has been used to infer neap-spring tidal cycles in three examples of widely different lithologies and thicknesses from the Lady Loretta Formation and provides convincing evidence of tidal deposition.

5.4 TIDAL RHYTHMITES

5.4.1 Description from Literature

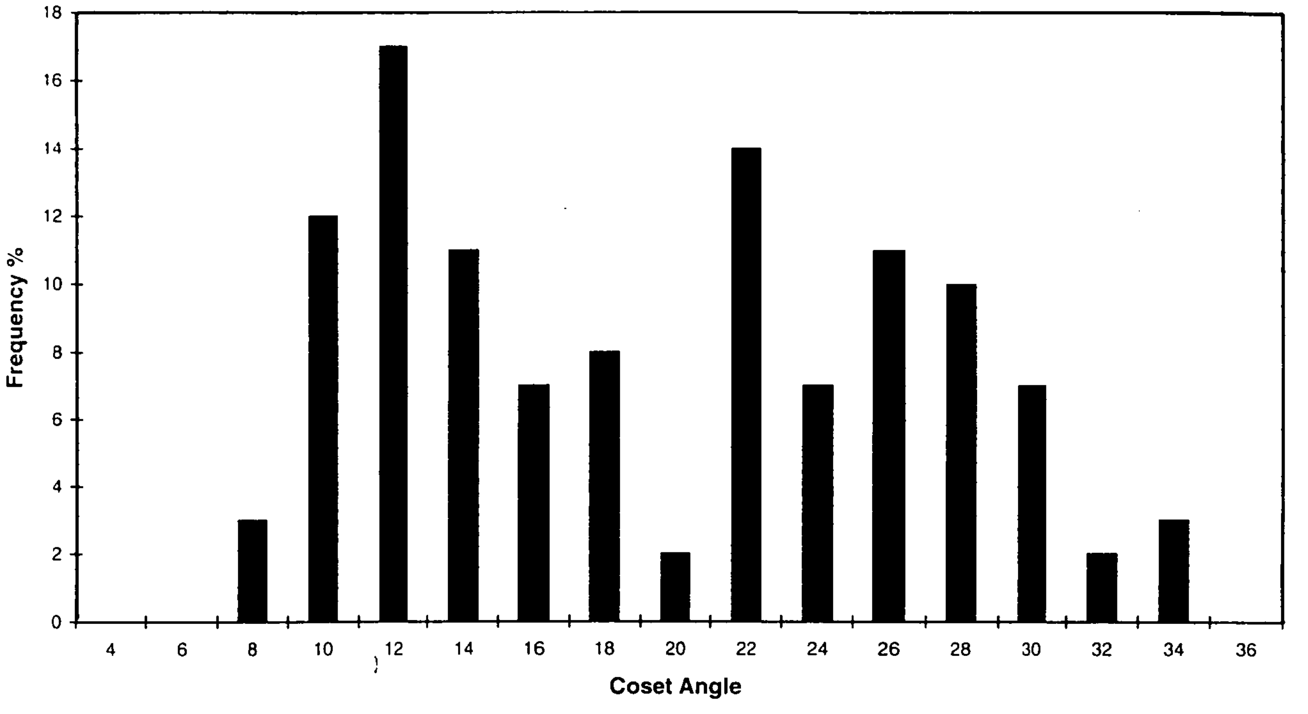
The term "tidal rhythmites" refers to vertically stacked beds that show cyclic changes in layer thickness due to neap-spring variations in tidal current speed (Dalrymple, 1992). They have also been referred to as "pin-stripe tidal bedding" or "ribbon rock" and commonly grade laterally to less-ordered tidal bedding such as lenticular and flaser bedding. Both modern examples and ancient analogues are described by Dalrymple *et al.* (1991), Klein (1985), Kvale and Archer (1990) and Williams (1991). The extensive literature on the subject is summarised in Appendix A-10.4 and it is interesting to note that several examples originally thought to be glacial or lacustrine varves have been reinterpreted as tidalites.

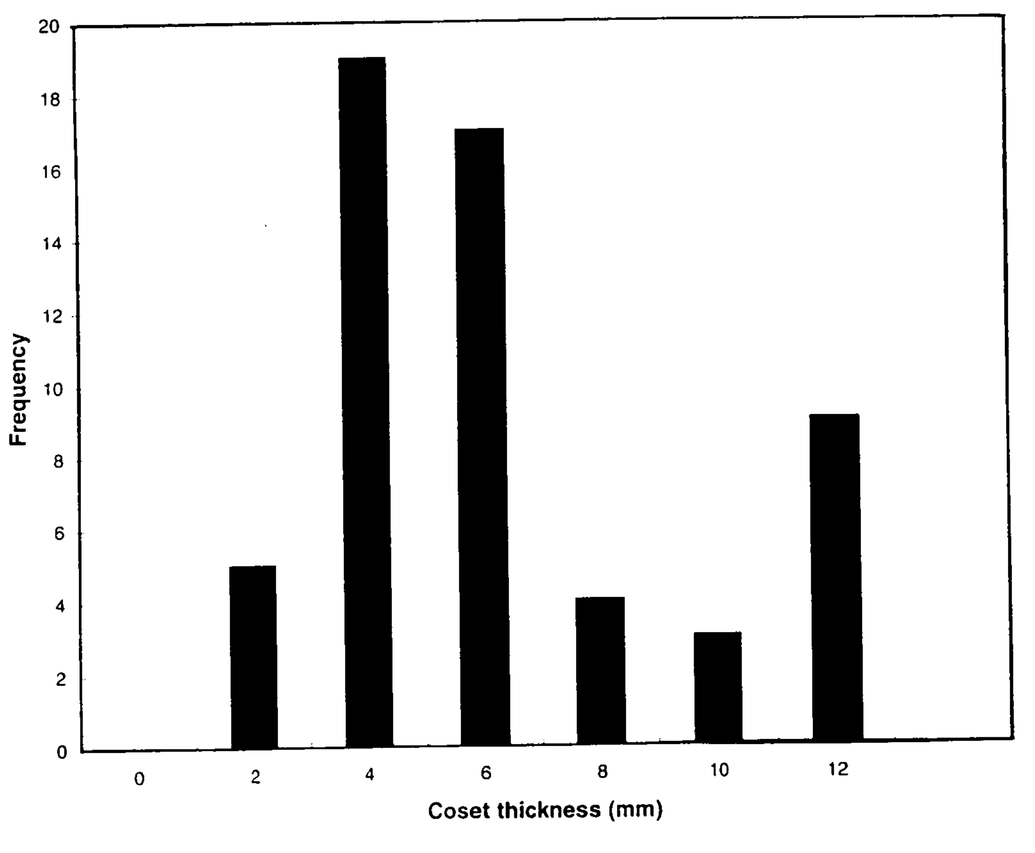
5.4.2 Examples from the Lady Loretta Formation

The Lady Loretta Formation contains several good examples of non-random vertical arrangements of bed thickness. These include parallel laminated sediments and the foresets of crossbeds at various scales as described in detail in Appendix A-10.4.

Figure 5-4: Bimodal distribution of crossbed dip angles from Gundaria Bore, n = 114.

Figure 5-5: Bimodal statistical distribution of coset thickness in the KD1A section, n = 57.


Frequency %
18
16
14
12
10
8
6
4
2
0
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
Coset Angle


Frequency
20
18
16
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
Coset thickness (mm)

5.4.3 Interpretation

The origin of tidal rhythmites was demonstrated in a field experiment by Reineck and Wunderlich (1968) who used different coloured dye markers to record deposition during each incoming and outgoing tide over a number of cycles. In the mid-tidal flat, a thin couplet of sand and mud was deposited during each tidal cycle and stacked couplets were preserved during subsequent tides. Since there was no bioturbation of pre-Neoproterozoic sediments, such tidal rhythmites are even more likely to be preserved.

Examples from the Lady Loretta Formation at Kamarga Dome are interpreted as having formed as stacked almost horizontally-bedded tidal rhythmites. Other non-random arrangements of foreset bed thickness are also interpreted as tidal rhythmites.

5.5 BIMODAL, BIPOLAR PALAEOCURRENT DATA

The study of palaeocurrent data was an important facet in understanding the sedimentology of the Lady Loretta Formation and considerable field work was necessary to obtain sufficient quantitative data without introducing a sampling bias. The methodology is described in Appendix A-2. The present study concentrated on palaeocurrent vectors determined from the foreset dip of crossbeds. This was augmented by the trends of ripples, preferred orientation of microbialites and several other indicators of palaeocurrent direction. In the following discussion, the regional data will be compared with that obtained from the vicinity of the Lady Loretta mine.

5.5.1 Regional Palaeocurrent Data from Crossbeds

Palaeocurrent data derived from the measurement of maximum crossbed dip have been grouped into three broad lithostratigraphic units. The sandstones near the contact of the Esperanza and Lady Loretta Formations and the lower Lady Loretta Formation are plotted in Figure 5-6. Palaeocurrent directions from the greater part of the Lady Loretta Formation; including carbonate, siliciclastic and mixed lithologies; are shown in Figure 5-7. The sandstones and coarser clastics in the transition zone to Shady Bore Quartzite provide ample opportunity for determination of palaeocurrent measurement and the results are shown in Figure 5-8. In addition, several dozens of measurements (not presented here) were made in the Esperanza Formation and Shady Bore Quartzite for comparison purposes.

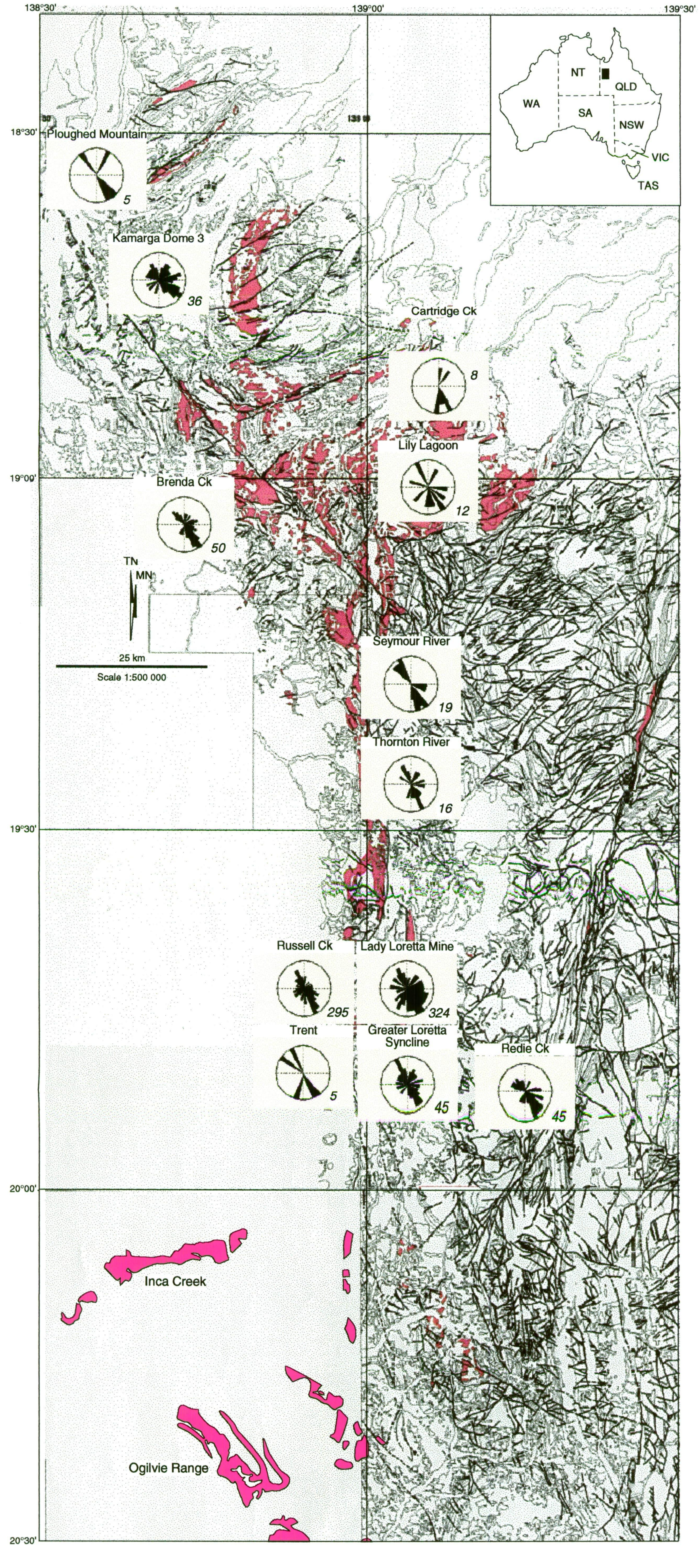
5.5.2 Regional Palaeocurrent Data from Ripples

As part of the ripple analysis presented in Appendix A-11, the trends of ripples in outcrop were plotted as bidirectional rose diagrams (Figure 5-9). Sites were chosen to augment the measurements made from the foresets of crossbeds.

Figure 5-6 (fold-out): Palaeocurrent directions determined from the dip of crossbed foresets in the lower Lady Loretta Formation.

138°30'
139°00'
139°30'
18°30'
19°00'
19°30'
20°00'
20°30'
NT
QLD
WA
SA
NSW
VIC
TAS
Kamarga Dome 5
24
Kamarga Dome 4
30
TN
MN
25 km
Scale 1:500 000
Russell Creek
96
Inca Creek
Ogilvie Range

Figure 5-7(fold-out): Palaeocurrent directions determined from the dip of crossbed foresets in carbonate, siliciclastic and mixed lithologies in the mid- Lady Loretta Formation.



138°30'
139°00'
139°30'
18°30'
19°00'
19°30'
20°00'
20°30'
NT
QLD
WA
SA
NSW
VIC
TAS
Ploughed Mountain
5
Kamarga Dome 3
36
Cartridge Ck
8
Lily Lagoon
12
Brenda Ck
50
TN
MN
25 km
Scale 1:500 000
Seymour River
19
Thornton River
16
Russell Ck
295
Lady Loretta Mine
324
Trent
5
Greater Loretta Syncline
45
Redie Ck
45
Inca Creek
Ogilvie Range

Figure 5-8(fold-out): Palaeocurrent directions determined from the dip of crossbed foresets in the transition zone to Shady Bore Quartzite.

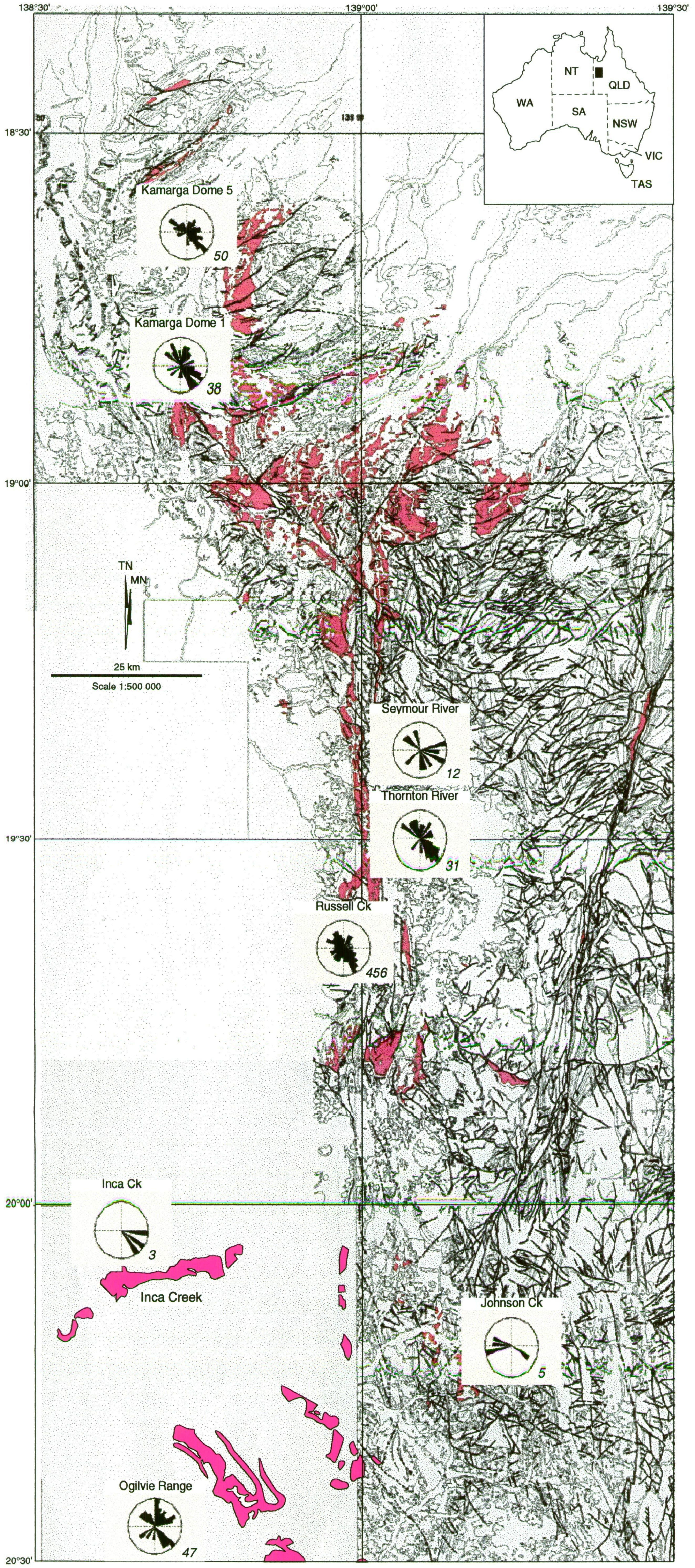
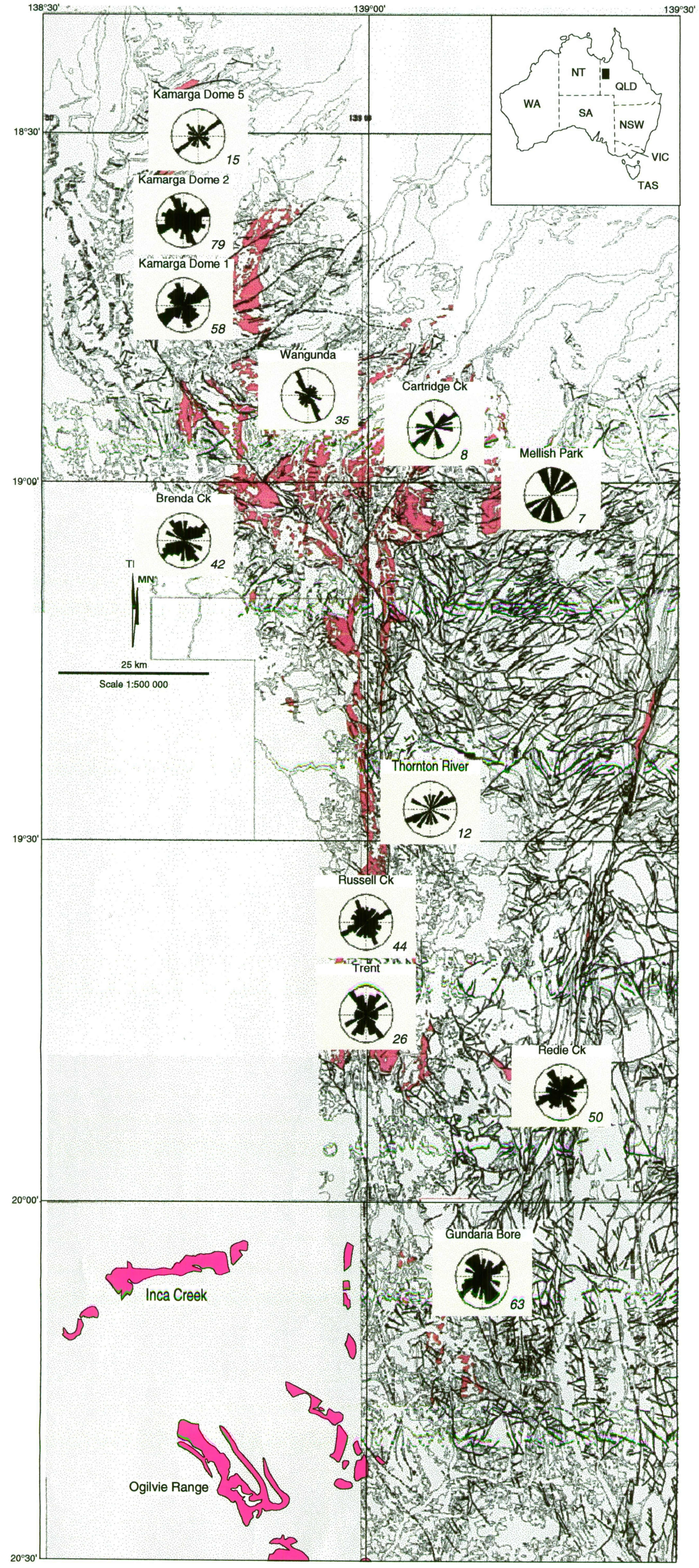

138°30'
139°00'
139°30'
18°30'
19°00'
19°30'
20°00'
20°30'
NT
QLD
WA
SA
NSW
VIC
TAS
Kamarga Dome 5
50
Kamarga Dome 1
38
TN
MN
25 km
Scale 1:500 000
Seymour River
12
Thornton River
31
Russell Ck
456
Inca Ck
3
Inca Creek
Johnson Ck
5
Ogilvie Range
47

Figure 5-9 (fold-out): Bidirectional plots of the orientation of ripples in the Lady Loretta Formation.



138°30'
139°00'
139°30'
18°30'
19°00'
19°30'
20°00'
20°30'
NT
QLD
WA
SA
NSW
VIC
TAS
Kamarga Dome 5
15
Kamarga Dome 2
79
Kamarga Dome 1
58
Wangunda
35
Cartridge Ck
8
Mellish Park
7
Brenda Ck
42
MN
25 km
Scale 1:500 000
Thornton River
12
Russell Ck
44
Trent
26
Redie Ck
50
Gundaria Bore
63
Inca Creek
Ogilvie Range

5.5.3 Other Palaeocurrent Indicators

Other indicators of palaeocurrent direction, shown in Figure 5-10, are the:

- alignment and inclination of microbialites
- dips of reactivation surfaces in demonstrably tidal sediments
- trends of gutter casts
- thickening of domains of imbrication in plate breccias
- trends of palaeo-channels and washout rills
- trends of sole and flute marks.

5.5.4 Interpretation of Regional Palaeocurrent Directions

The palaeocurrent data determined from crossbeds throughout the Lady Loretta Formation regionally are clearly bimodal and bidirectional with northwest and southeast trends. In the majority of locations, the trend toward the southeast is dominant. In some cases, particularly from the upper and mid Lady Loretta Formation there also appears to be a subsidiary component from the west.

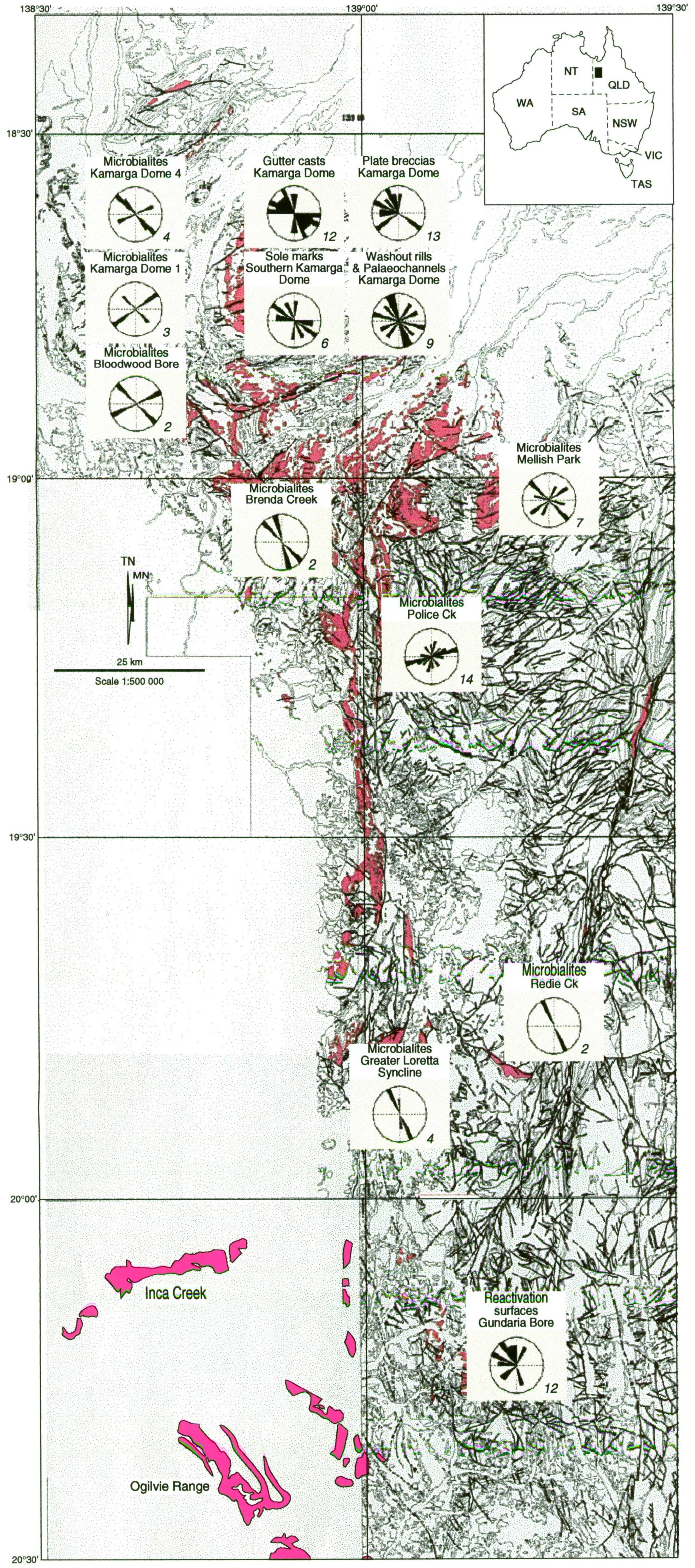
The trends of ripples have a strong east-northeast west-southwest component with a subsidiary trend at right angles. These orientations can be interpreted to suggest that the majority of ripples formed under the same hydraulic regime that produced the dominant trend of crossbeds. Microbialite alignment and inclination parallels the trends of the ripples, although the dominant trend varies from one location to another. These relationships are consistent with Young and Long (1976) who also found that elongate Proterozoic microbialites were oriented parallel to bimodal bipolar palaeocurrents determined from crossbedding and crosslamination. The thickening of plate breccias to the northwest may be interpreted to indicate the direction of onshore directed storm surge. This is corroborated by the northwest-southeast trend of the gutter casts which are also interpreted as storm deposits (see Section 7.5). As described in Section 5.3.2, the dip of tidal reactivation surfaces can be interpreted to suggest that the dominant tide was toward the north to northwest. The trends of washout rills, palaeochannels and sole marks from Kamarga Dome are also consistent with northwest or southeast directed flow.

Thus, the palaeocurrent data from the Lady Loretta Formation regionally are consistent with a northwest-southeast tidal influence. It may be tentatively interpreted that the shoreline ran at rightangles to this, shallowing to the northwest. However, such as interpretation may be an oversimplification since some modern analogues have the dominant palaeocurrents directed alongshore.

5.5.5 Palaeocurrent Data from the Vicinity of the Mine

The palaeocurrent data from outcrop in the vicinity of the Lady Loretta mine are shown geographically in Figure 5-11. Figure 5-12 is a lithostratigraphic breakdown through the uppermost Lower Carbonate Unit to the Cyclic Unit. As discussed in Appendix A-11, it is also possible to demonstrate 180º opposed ripple foresets in core.

Figure 5-10 (fold-out): Other palaeocurrent indicators in the Lady Loretta Formation regionally.



138°30'
139°00'
139°30'
18°30'
19°00'
19°30'
20°00'
20°30'
NT
QLD
WA
SA
NSW
VIC
TAS
Microbialites
Kamarga Dome 4
4
Gutter casts
Kamarga Dome
12
Plate breccias
Kamarga Dome
13
Microbialites
Kamarga Dome 1
3
Sole marks
Southern Kamarga
Dome
6
Washout rills
& Palaeochannels
Kamarga Dome
9
Microbialites
Bloodwood Bore
2
Microbialites
Mellish Park
7
Microbialites
Brenda Creek
2
TN
MN
25 km
Scale 1:500 000
Microbialites
Police Ck
14
Microbialites
Redie Ck
2
Microbialites
Greater Loretta
Syncline
4
Inca Creek
Reactivation
surfaces
Gundaria Bore
12
Ogilvie Range

Figure 5-11: (fold-out): Map showing the palaeocurrent directions measured in the vicinity of Lady Loretta Mine.

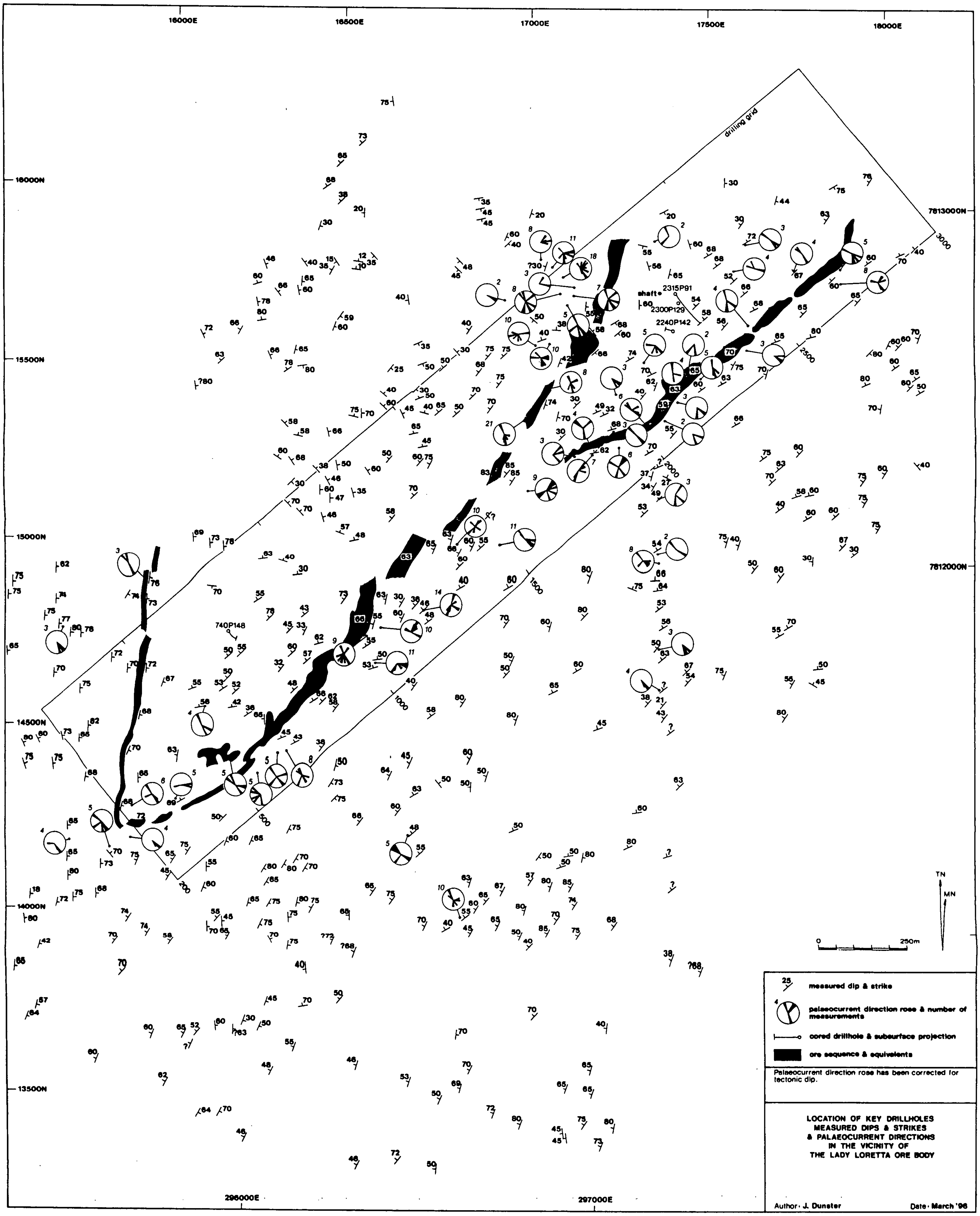
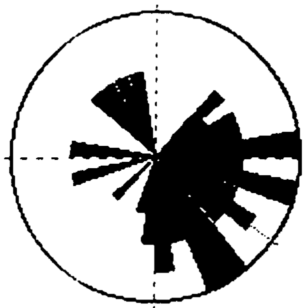

16000E
16500E
17000E
17500E
18000E
16000N
15500N
15000N
14500N
14000N
13500N
7813000N
7812000N
296000E
297000E
drilling grid
3000
2500
2000
1500
1000
500
200
shaft
2315P91
2300P129
2240P142
740P148
TN
MN
0
250m
measured dip & strike
palaeocurrent direction rose & number of measurements
cored drillhole & subsurface projection
ore sequence & equivalents
Palaeocurrent direction rose has been corrected for tectonic dip.
LOCATION OF KEY DRILLHOLES
MEASURED DIPS & STRIKES
& PALAEOCURRENT DIRECTIONS
IN THE VICINITY OF
THE LADY LORETTA ORE BODY
Author: J. Dunster
Date: March '96

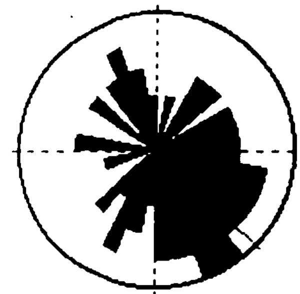
Figure 5-12: Palaeocurrent data from the vicinity of the Lady Loretta mine; shown in total and as a lithostratigraphic breakdown.

Cyclic Unit



116

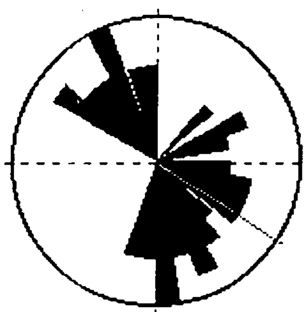
Overall



352

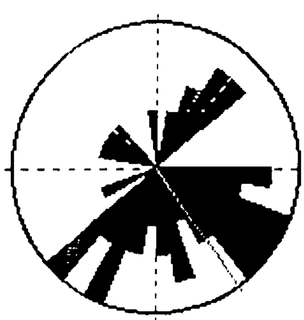
Class: 10
Max Percent: 7
Vector Mean: 134°
Vector Magnitude: 103
Consistency Ratio: 0.32

Ore Sequence / Ore Sequence Equivalent



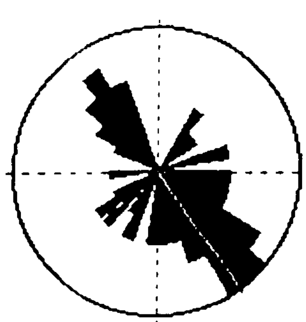
50

Pyritic Unit



102

Undifferentiated footwall sequence



84

5.5.6 Interpretation of Palaeocurrent Directions from the Vicinity of the Mine

Overall, the palaeocurrent directions measured in the vicinity of the Lady Loretta mine are similar to those from the formation regionally. They do not support either of the sedimentary models previously proposed for the mine. There is no evidence of uni-directional flow directed away from a fault scarp on the Carlton Fault Zone as suggested by Lee (1972). Similarly, the concept that the Small Syncline was an isolated basin with inwardly directed flow (Lee, 1972: Lemcke, 1986) cannot be sustained.

5.6 RIPPLE ANALYSIS

The Lady Loretta Formation contains a wide diversity of different ripple morphologies. These were studied both qualitatively and quantitatively (Appendix A-11). Interference and ladder-back ripples are interpreted as shallow-water tidal deposits. Features such as planed and double crested ripples are diagnostic of shallowing up to near emergence (Allen, 1982). As documented in Appendix A-11, wave ripples are common throughout the formation regionally and also occur in the vicinity of the mine. These contain a range of internal structures (*e.g.* opposed bidirectional lenses of different sizes, bundled and chevron up-building) diagnostic of shallow-water tidal deposition (de Raaf *et al.*, 1977). Application of the Clifton - Dingler (1984) equations based on measurements of ripple morphology to estimate palaeo-water depth is dubious (see Section A-11.3.2). However, the results from the Lady Loretta Formation may be taken to indicate no significant difference in water depth between the mine and the formation regionally. Proponents of this technique would infer relatively shallow conditions in both cases (see Appendices A-11.4.4 and A-11.5.3).

5.7 SEDIMENTARY EVIDENCE OF VERY SHALLOW CONDITIONS OR EMERGENCE

5.7.1 Washout Rills and Scour Pits

Description

Washout rills are typically shallow (<2 cm), usually small scale, dendritic erosional channels. Their wide diversity of form is described in Reineck and Singh (1980). Examples from the Lady Loretta Formation wash out ripple pavements and form microdeltas (Figure 5-13a).

Scour pits are similar features forming as small depressions. They are commonly floored by current or interference ripples. Scour pits are most abundant in the clastic-dominated facies in the transition to Shady Bore Quartzite. Examples with superimposed lunate and planed current ripples are exposed on exhumed bedding surfaces in Russell Creek.

Interpretation

Washout rills originate when a thin film (< 2 cm) of water flows over a sediment surface and, as such, they are associated with the change from subaqueous to subaerial

Figure 5-13: (a) Washout rill on a ripple pavement. The dendritic channel drained right to left down the beach and back to the sea, excising progressively deeper through the ripples. Along strike, the same ripple pavement contains small halite hoppers and synaeresis cracks in the swales between ripples. (b) Wrinkle marks and larger synaeresis cracks, PHP252. (c) Tristar synaeresis cracks confined to the swales between ripples. Note the association with halite casts (arrowed), SER237A. (d) Sinusoidal synaeresis cracks in swales between ripples. From the Lady Loretta Formation / Shady Bore Quartzite transition at Kamarga Dome. (e) Tristar synaeresis cracks approaching a network. From the Big Syncline, Lady Loretta mine, LLD396. (f) Network of synaeresis cracks, Brenda Creek. (g) Spindle and tristar synaeresis cracks in chert, Phosphate Plant. (h) Spindle and tristar synaeresis cracks in a prone microbial fabric, Kamarga Dome. Coin is 3 cm d and bar scale is 1 cm.


a
b
c
d
e
f
g
h

conditions. Modern examples are ubiquitous on tidal flats and beaches where they wash out ripple pavements; they also occur on longshore bars, on river banks and flood plains after a flood, or from flow in an otherwise dry terrestrial environment. Washout rills are common in the stratigraphic record, where their significance is primarily as indicators of exposure (Allen, 1984).

Klein (1977) described the formation of scour pits and the superimposed current ripples as part of the normal spectrum of bedforms developed as both tidal flats and intertidal sand bodies are exposed by falling water levels.

Examples from the Lady Loretta Formation are good evidence of very shallow conditions in a tidal environment.

5.7.2 Millimetre Ripples

Description

Reineck and Singh (1980) use the term "millimetre ripples" for almost straight-crested miniature ripples with mostly flattened crests, where troughs and crests are equally broad (2-5 mm) and the height of the crests is less than 1 mm. Such ripples are only surface forms and do not possess any internal structure. They differ from wrinkle marks in the regularity of their crests (Singh and Wunderlich, 1978).

Millimetre ripples occur as modifications of crests and troughs of true ripples in exposures of the Lady Loretta Formation at Brenda Creek (sample BCC008) and Kamarga Dome where they are associated with halite casts and synaeresis cracks in the larger ripple troughs.

Interpretation

Millimetre ripples are commonly thought to be indicative of subaerial emergence from very shallow water (1-3 cm deep, Singh & Wunderlich, 1978). Modern examples that piggy-back larger ripples occur on beaches and in ephemeral outwash channels. However, Jennette and Pryor (1993) also found millimetre ripples in storm-dominated shallow subtidal Ordovician sediments. They favoured Duke's (unpublished) explanation that such ripples reflect immature, disequilibrium wave ripples generated by very low-speed flows that might be independent of water depth. By analogy with modern examples, and because of the association with halite and synaeresis cracks, the current study favours the original interpretation for examples from the Lady Loretta Formation, *i.e.* very shallow to emergent conditions.

5.7.3 Wrinklemarks

Description

Wrinkle- or runzlemarks are miniature, irregular ripple-like features, consisting of ridges 0.5 to 1.0 mm thick and a few millimetres in length. The smallest examples (<1 mm across, sample BCC008) from the Lady Loretta Formation occur on the flanks of wave ripples associated with halite casts and millimetre ripples. They are better developed on the lee side of the ripples. Larger examples cap dolomitic siltstone beds and extend laterally for several metres (Figure 5-13b). The example illustrated is broken into polygons by synaeresis cracks. When viewed in section; neither it, nor the overlying bed, have discernible microbial fabrics.

Interpretation

Wrinklemarks, similar to the smallest examples from the Lady Loretta Formation, occur on modern intertidal flats and are usually taken as a good indicator of intermittent emergence. Sand being plucked from the surface by windblown seafoam (Kocurek and Fielder, 1982), disfigured rainprints (Clifton, 1977; Klein, 1977, 1985) and a form of load cast restricted to the intertidal zone (Allen, 1985) have been previously proposed as likely origins. However, in comparison with modern examples shown in Kocurek and Fielder (1982) and Smoot and Castens-Seidell (1994) and the discussion in Demicco and Hardie (1994), the present study interprets the small scale wrinkle marks as resulting from wind blown sand and silt adhering to a thin efflorescent salt crust. This is consistent with their restriction to one side of the ripples and the association with halite casts.

The larger wrinklemarks from the Lady Loretta Formation (sample PHP252 - Figure 5-13b) resemble small salt blisters ("puffy ground") on salt pans in Death Valley (Scholle and James, 1995). They are also similar to (but smaller than) halite-encrusted desiccated algal mat from the lower parts of supratidal zone on the Abu Dhabi coastline. This surface is also broken into irregular polygons (Scholle and James, 1995, image 331).

In all these cases, wrinkle marks are indicators of emergence.

5.7.4 Shrinkage Structures: Desiccation, Synaeresis, Diastasis Cracks and Pull-Apart Structures

Terminology and Description from Literature

Mudcracks, which have conspicuous modern analogues as desiccation features, can be subdivided into orthogonal or non-orthogonal arrangements. The former have perpendicular junctions, tending to form four sided polygons; the latter have triple junctions commonly outlining hexagonal polygons. Orthogonal forms occur in a great variety of marine and non-marine environments; the non-orthogonal type occurs in sediment that is homogeneous and relatively brittle where shrinkage is uniform. They may be over-represented in the literature in comparison to orthogonal forms (Lindholm, 1987).

Demicco and Hardie (1994) stressed that mudcrack infill must be a result of infiltration from above. Shinn (1983, 1986) noted that mudcracks in modern carbonates are generally different from those in clays. Both begin as V-shaped cracks, but cracks in carbonates become rounded and the resulting polygons can appear as sausages in cross-section.

Synaeresis cracks are thought to form in the subaqueous environment due to clay volume changes resulting from syndepositional compaction of a settling clay layer, rapid flocculation or increase in pore-water salinity (Demicco and Hardie, 1994). In plan, synaeresis cracks are typically lenticular and discontinuous. In at least some cases referred to by Demicco and Hardie (1994) the material infilling the synaeresis cracks may have come from below, not from above as in desiccation cracks. Although synaeresis cracks are relatively common in the stratigraphic record (Plummer and Gostin (1981) illustrated Proterozoic examples) and can be produced in laboratory experiments, there is a dearth of documented modern analogues.

Diastasis cracks (also called pull-apart structures) are produced by mechanical deformation at or just beneath the seafloor but are not diagnostic of any particular water depth.

Observations from the Lady Loretta Formation, Interpretation and Discussion

The past six years have seen a renewed debate about the interpretation of various types of shrinkage cracks in the stratigraphic record and it is possible that many ancient examples have been misinterpreted (see Astin and Rogers, 1991, 1993; Cowan and James, 1992; Barclay *et al.*, 1993; Bull, 1996a). Demicco and Hardie (1994) critically reviewed the literature and concluded that "the commonly cited criteria used to distinguish subaerial desiccation mudcracks are equivocal at best." They were also of the opinion that synaeresis cracks described from the rock record were "inadequate and untrustworthy" and recommended discontinuation of the term's usage. Examples from the Lady Loretta Formation, described below, may shed some new light on this problem.

Desiccation cracks have previously been reported from the Brenda Creek area (Dorrins *et al.*, 1983; McConachie pers. comm., 1996), Kamarga Dome (Pringle and David, 1983) and the Lawn Hill region (Sweet and Hutton, 1980,1982). They are preserved in outcrop as cracks or, less commonly, positive relief casts. Figure 5-14a-h illustrates examples from the Lady Loretta Formation interpreted as desiccation cracks. The bedding surface shown in Figure 5-14c is a typical outcrop example that has wider and longer through-going orthogonal cracks. Smaller subsidiary non-orthogonal cracks form a network. Figure 5-14d shows a tile form a desiccation pavement. The orthogonal borders of the tile were probably more pervasive desiccation cracks or tepees. Possible desiccation cracks have also been interpreted in core, Figure 5-2d shows an example.

The cracks shown in Figure 5-14a are from a few metres stratigraphically above the Ore Sequence Equivalent in the Big Syncline. This outcrop is along strike from the desiccation-cracked mudstone containing evaporite pseudomorphs illustrated by McGoldrick (1993). The cracks trend toward orthogonal at the top of the photograph, but the majority intersect at triple junctions. Smaller examples of mudcracks from the vicinity of the Lady Loretta mine are shown in Figure 5-14b and g. Subsidiary and incipient cracks are present and, again, the intersections are dominantly triple junctions.

These desiccation cracks are taken as evidence of subaerial exposure during deposition of the Lady Loretta Formation and, commonly, this interpretation can be corroborated by other sedimentological evidence.

Figure 5-14: Desiccation cracks form the Lady Loretta Formation. (a) Probable mudcracks from the Big Syncline, Lady Loretta mine, LLD201. (b) Close up of small mudcracks from the vicinity of the Lady Loretta mine, LLD199A. (c) Desiccation cracks in outcrop of the Lady Loretta Formation at Thornton River. Note the polygonal network and larger, through-going, cracks outlined on the right. (d) A tile from a desiccation pavement. The edges of the slab were probably larger desiccation cracks or tepees. (e) and (f) Poorly preserved desiccation cracks, REC73. (g) Small mudcracks from the vicinity of the Lady Loretta mine, LLD199B. (h) Mudcracks or synaeresis cracks from Inca Creek, INC274.

Coin is 3 cm d and bar scale is 1 cm.


a
b
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Synaeresis-type cracks are widespread in the Lady Loretta Formation and ubiquitous in the transition to Shady Bore Quartzite. It is interesting to note that, in comparison to desiccation cracks, synaeresis cracks in the Lady Loretta Formation are most commonly preserved in positive relief. Examples from the Lady Loretta Formation can be described as:

- isolated spindle shapes
- tristars
- networks
- sinusoidal.

This order also approximates to decreasing order of abundance. Isolated spindles and tristars are illustrated in Figure 5-13c,e,g,h. Where tristars are sufficiently abundant, they form a network (Figure 5-13f).

Another unusual form of synaeresis crack is locally common in dolomitic facies of the Shady Bore Quartzite at Kamarga Dome, but was not recorded from the Lady Loretta Formation as shown on published maps. Cracks close in all directions so that they resemble small open tension gashes in section. This type of crack occurs randomly over several decimetres throughout the bed and has no preferred orientation (which excludes a mechanical origin). They are similar to other Proterozoic features described by Horodyski (1976) and Knoll and Swett (1990) who interpreted them as synaeresis cracks. In contrast to the opinions of Demicco and Hardie (1994), these examples are not associated with a desiccation surface and may be true intra-sediment shrinkage features.

In comparison to desiccation cracks, there are no large through-going features in synaeresis cracks and many of the cracks are distinctly curved. Nor are there any smaller subsidiary features to produce a fractal effect. Sample LLD396, shown in Figure 5-13e, is significant in that it comes from the Big Syncline at the Lady Loretta mine. Carr (pers. comm., 1995) also reported possible synaeresis cracks in outcrop of the Ore Sequence.

The sinusoidal example illustrated in Figure 5-13h is typical of features developed in the transition zone from Lady Loretta Formation to Shady Bore Quartzite. Similar features were also observed in the arenaceous facies of the Esperanza Formation. In many cases there is also a close association with small halite casts (Figure 5-13c). This sinusoidal form seems exclusively restricted to the swales between ripples. Had these rocks been Palaeozoic, the curved casts could easily have been interpreted as trace fossils. Demicco and Hardie (1994) described spindle-shaped synaeresis cracks from swales between ripples and attributed them to downslope creep. The sinusoidal forms in the Lady Loretta Formation are unlikely to have formed this way. Since they do not have any of the features of mudcracks arising by desiccation, these examples may be true subaqueous shrinkage cracks.

Another important observation from the Lady Loretta Formation is that synaeresis cracks are commonly restricted to small palaeo-topographic depressions such as swales between ripples or scour pits.

Probable diastasis cracks occur associated with other features of mechanical deformation of soft sediment in core from the vicinity of the Lady Loretta mine and in outcrop of interbedded dolostone and dolomitic siltstone from Brenda Creek. Diastasis cracks are also present in the core from drillhole Amoco 83-5. These occurrences are of no palaeo-environmental significance other than indicating subaqueous deposition.

5.7.5 Microkarst

Possible microkarst surfaces were identified in carbonates in the Brenda Creek (Sweet *et al.*, 1993; Southgate, pers. comm., 1995), Bloodwood Bore and Kamarga Dome sections. The surfaces are defined by unusual solution collapse breccias up to a metre thick or by mini-unconformities where there was variable erosional relief on the top of one carbonate bed before the deposition of the next. This erosion commonly resembles the rillenkarren produced by chemical weathering. Even in reasonable outcrop, these surfaces could not be traced for any more than a few tens of metres laterally and appear to grade to zones of intense pressure solution.

Another example, near the KD2 field section was probably first recognised by Pringle and David (1983). Here, small steep-sided fissures 8-10 cm across grade down over about 75 cm to near-vertical fractures about a centimetre wide. They are infilled by layered oxidised sediment similar to terra rosa but because the overlying unit is not well exposed it was impossible to be sure that these features are truly intraformational.

Microkarst is good evidence of subaerial exposure. However, these examples from the Lady Loretta Formation are equivocal at best and do not appear to be of regional significance. The occurrence of true microkarst features may be underestimated because they seem to be the focus of later pressure solution. They would be very difficult to detect in core. By analogy to other basins where the karst surface consists of carbonate on carbonate, interpretations of gamma logs alone may not identify the surface.

If the presence of laterally extensive evaporite pseudomorphs can be used to infer a relatively arid climate (see Chapter 9), then it is not surprising that subaerial karst, normally associated with wetter climates, is not a major feature in the Lady Loretta Formation.

5.8 SUMMARY

Regionally, the Lady Loretta Formation contains convincing evidence of at least sporadic tidal deposition and this helps confirm a marine setting. Similar features were observed beneath the level of the Ore Sequence at Lady Loretta mine.

Evidence of subaerial exposure is widespread throughout the formation and the lateral facies equivalents of the Ore Sequence contain desiccation and synaeresis cracks.

Chapter 6 - Agitated Water Deposits - Coated Grain Fabrics

6. AGITATED WATER DEPOSITS - COATED GRAIN FABRICS

6.1 INTRODUCTION

Coated grain fabrics are one of the most-intensively studied of all carbonate textures and have been reviewed by Simone (1980) and Peryt (1983). These textures were described from the Lady Loretta Formation because ooids have well-documented modern equivalents, are potentially good palaeoenvironmental indicators of both chemical and physical conditions, and are particularly useful in studying carbonate diagenesis (see Section 11.4.6). The present study also addresses two other controversial aspects of coated grain fabrics from the Lady Loretta Formation:

- what significance can be put on the unusual sizes of some of the chemically precipitated coated grains?
- can the morphology and trace element composition of the coated grains be used to infer the original carbonate mineralogy (dolomite, calcite or aragonite)? This was discussed in Section 4.2.

6.2 TERMINOLOGY - OOIDS, PISOIDS, ONCOIDS AND AGGREGATE GRAINS

Any glossary of geology will list a confusing plethora of terms for coated carbonate grains and the rocks composed of them. Alternate classifications were proposed by Flügel (1982) and Peryt (1983) and discussed in Tucker and Wright (1990). The present study has slightly modified the simplest formal classification from Flügel (1982), in which, an "ooid" is defined as a regularly formed, more or less spherical or ellipsoidal, carbonate particle with uniform concentric laminae coating a nucleus. In thin-section, tangential and/or radial structures can be recognised in the laminae. All authors agree that ooids form by chemical precipitation, but a few also argue for a biological contribution (see discussion in Tucker and Wright, 1990). In the English literature, ooids are commonly defined as less than 2 mm in diameter. A "pisoid" is defined as a conspicuously regular coated grain greater than 2 mm in diameter consisting of concentric micritic laminae. They are generally thought of as forming by chemical precipitation and some authors would restrict the term to a non-marine origin. In contrast, an "oncoid" is irregularly formed with non-concentric, partially overlapping, micritic laminae. They are formed by biogenic deposition around a nucleus, itself generally larger than 2 mm diameter. The nucleus commonly forms more than half the total diameter. "Aggregate grains" are irregularly-shaped, lobed aggregates of particles bound and/or coated by either carbonate cement or microbial/algal lamination. This includes "grapestones," "botryoidal lumps" and "compound ooids" in which one or more ooids are bound together with an internally-laminated chemically precipitated envelope.

Several workers (*e.g.* Swett and Knoll, 1989) have pointed out that the distinction between ooids and pisoids at a grainsize boundary of 2 mm is arbitrary and that, in many instances, coated grains in both size ranges have formed by the same process in a marine environment. This led to the term "giant ooid" advocated by Sumner and

Grotzinger (1993) amongst others.

Despite being genetic terminology and ignoring the possible role of biological agents in ooid formation, the phase "chemically precipitated multi-coated grains" is used in this thesis to embrace all true marine and paralic ooids and larger, singular or compound, equivalents that formed by a similar process.

6.3 DESCRIPTION OF EXAMPLES FROM THE LADY LORETTA FORMATION

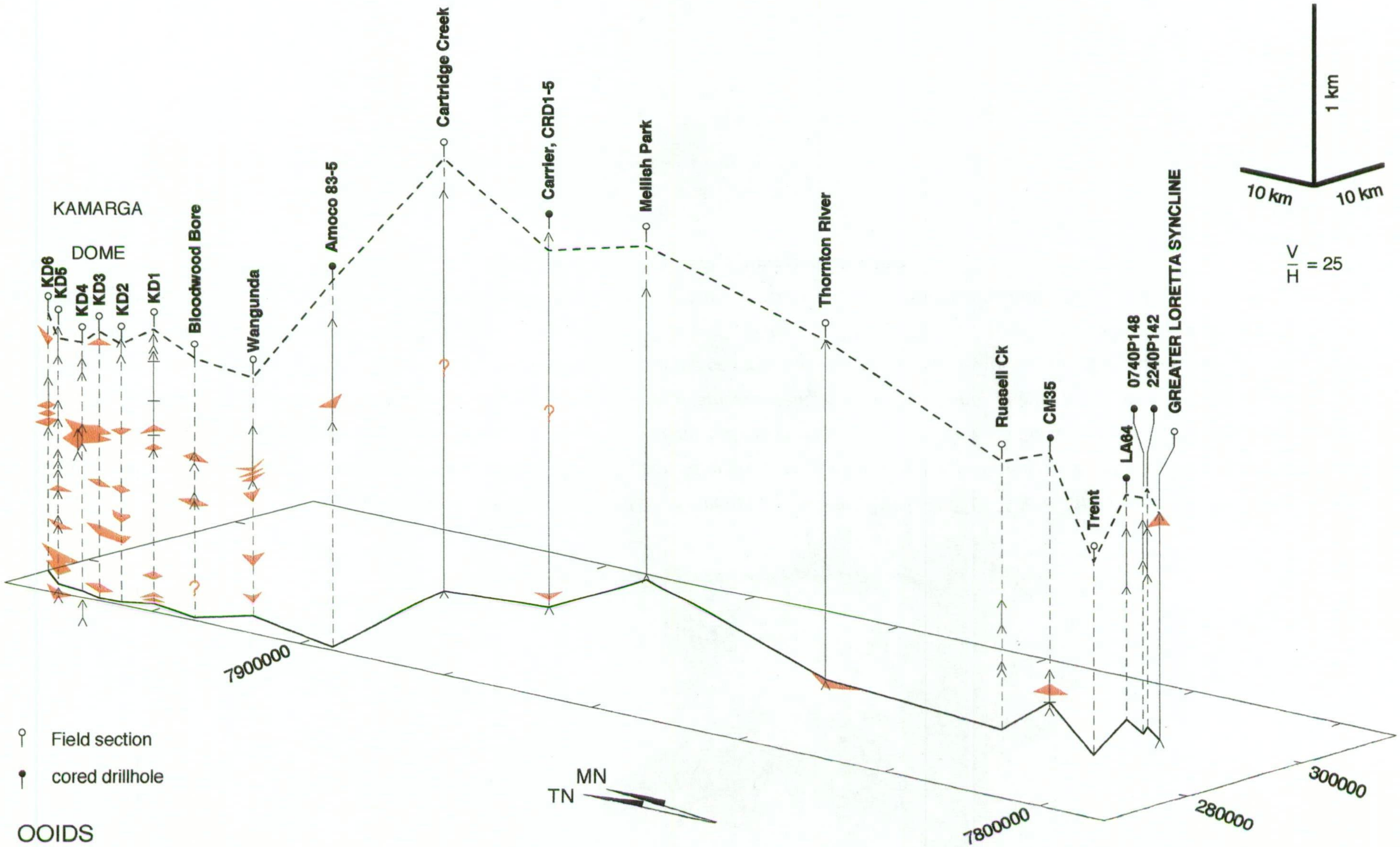
The Lady Loretta Formation contains numerous beds of chemically precipitated multi-coated grains. Examples from outcrop, noted during the regional mapping by the GSQ and BMR and in numerous unpublished company reports, are dolomite but invariably have been partially silicified. Even material from core is incipiently silicified.

Ooid grainstones are widespread at numerous lithostratigraphic levels within the Lady Loretta Formation (Figure 6-1) but individual beds are not laterally extensive. Grainstone beds in the area covered by the Lawn Hill 1:100 000 geological map are typically up to 1.8 m thick and contain a variety of different grainsizes. Locally, the beds are graded and well sorted. Both normal and inverse grading were observed. There are commonly conspicuous differences in grainsize between beds separated by only a few metres stratigraphically. Most beds consist almost exclusively of ooids, but some also contain rare oncoids and carbonate intraclasts including possible ripped-up microbial mat. Detrital clastic material is rare. Many of the beds are internally crossbedded and rippled; some have scoured bases. The thicker beds contain large scale cross-stratification. Bipolar bimodal palaeocurrent data were recorded from two examples at Kamarga Dome (see Section 5.5).

A previously undocumented, unusually well-preserved series of ooid/pisoid/ aggregate grain grainstone beds was mapped in the vicinity of the KD4 section at Kamarga Dome. Internally, the beds are variably reverse and normally graded and are now commonly in stylolitic contact. Individual beds range from well sorted to very poorly sorted. Examples from this area are shown in Figure 6-2a-f. Pendant and meniscus cements are present. Asymmetric coated grains and aggregate grains are common. In the latter case, up to 15 ooids are cemented together by a thick outer coat that resembles the cortex of other ooids/pisoids. Sphericities vary from 1:1:1 axial ratios to extremely elongate (1:1:7.5 *e.g.* Figure 6-2e). The most outstanding feature of these chemically precipitated coated grains is their large size, up to 8.33 mm and 12 mm were recorded in thin section and outcrop respectively.

Many of the central cross-sections reveal that the larger ooids/pisoids consist of three concentric zones. This is evident in the pisoids shown in Figure 6-2c and the central ooid in the compound grain in Figure 6-2f. The nucleus is typically small (<0.3 mm) and is commonly preferentially silicified. The next zone consists of relatively large radially-arranged crystals that do not extend all the way to the nucleus. The surrounding cortex is unusually thick. The individual cortical laminae thicken (from about 30μm to 80 μm) and become less symmetric towards the exterior. Some laminae are discontinuous and the

Figure 6-1: Distribution of ooid/pisoid grainstones in the Lady Loretta Formation.


KAMARGA
DOME
KD6
KD5
KD4
KD3
KD2
KD1
Bloodwood Bore
Wangunda
Amoco 83-5
Cartridge Creek
Carrier, CRD1-5
Mellish Park
Thornton River
Russell Ck
CM35
Trent
LA64
0740P148
2240P142
GREATER LORETTA SYNCLINE
1 km
10 km
10 km
V/H = 25
7900000
7800000
280000
300000
MN
TN
Field section
cored drillhole

OOIDS

Figure 6-2: Ooids and pisoids. (a) Ooid pisoid grainstone from section KD4, Kamarga Dome, sample KD4.357B. Different grainsizes are now separated by stylolites. Polished slab of vertical section. (b) Poorly sorted ooid pisoid oncoid grainstone as seen in outcrop, KD4 section. (c) Photomicrograph showing compound and asymmetric forms. Note the pendant cement beneath the grains and the meniscus cement between the two grains just left of center, sample KD1.352. Polarised light. (d) Photomicrograph of pisoid with asymmetric cortical laminae, sample KD1.352. Plane light. (e) Photomicrograph of an ovoid coated grain with pendant cement KD1.352. Plane light. (f) Compound ooid. Note that the coating is identical to the cortex of other ooids and pisoids with sweeping fan-like extinction under polarised light. Pendant cement is also clearly visible. KD4.357B. (g) and (h) Photomicrograph of ooid grainstone in polarised light and under cathodoluminescence. The latter illumination reveals concentric rings in the dark micritic area lower left, suggesting that it is probably another ooid/pisoid. Bar scales in (a) and (b) are 1 cm, remainder are 1 mm.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asymmetric protuberances are commonly out of phase (Figure 6-2c,d). The cortex displays a tangential-radial fabric, manifest as sweeping fans of undulose extinction under crossed nichols.

Beds of ooid grainstone, with a more typical size distribution, are present in all sections north of the Redie Creek field section. Carr (1981) described ooids and oncoids from the sandstone in the Big Syncline and illustrated an example from drillhole 1350P150 114.6 m. During the present study, float of a silicified and ferruginised ooid grainstone (possibly the same bed described by Carr, 1981) was traced about 50 m along one limb of the Big Syncline. Samples from here, such as LLD395, are the best-preserved coated grains from the vicinity of the mine.

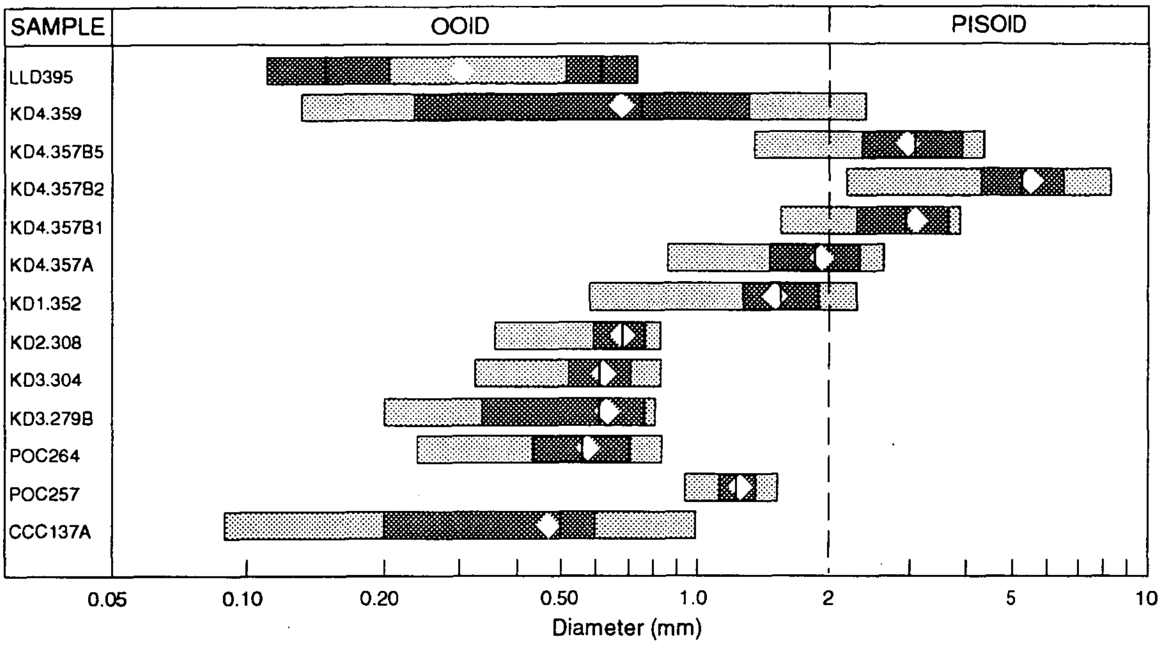
Representative samples from several locations were thin-sectioned and the diameters of the coated grains measured. Aggregate grains were excluded. As with any such study based on thin sections, the measurements are underestimates because relatively few of the grains will be seen as an axial section. This bias was corrected for means and medians using the empirically derived equations of Harrell and Eriksson (1979) but still precludes any rigorous statistical treatment of the data. The corrected results are shown in Table 6-1 and diagrammatically in Figure 6-3a. Note that there is a wide range of grainsizes including populations that fall within either the ooid or pisoid category and several that overlap the 2.0 mm boundary. The bimodal sample from the Big Syncline is the only unusual statistical distribution from those samples sectioned, but other bimodal populations were noted from elsewhere in the field. There is a correlation between coated grain diameter and the percentage of compound ooids by volume. Those samples with a maximum diameter of less than 1.0 mm lacked compound ooids. The percentage of compound ooids also appears to be related to the degree of sphericity of the single ooids/pisoids associated with them. Most compound ooids occur in association with asymmetric single forms.

In all examples studied from the Lady Loretta Formation, the coated grains are a closed framework in which the grains constitute more than 50% of the total rock volume. Packing is variable and not related to grainsize.

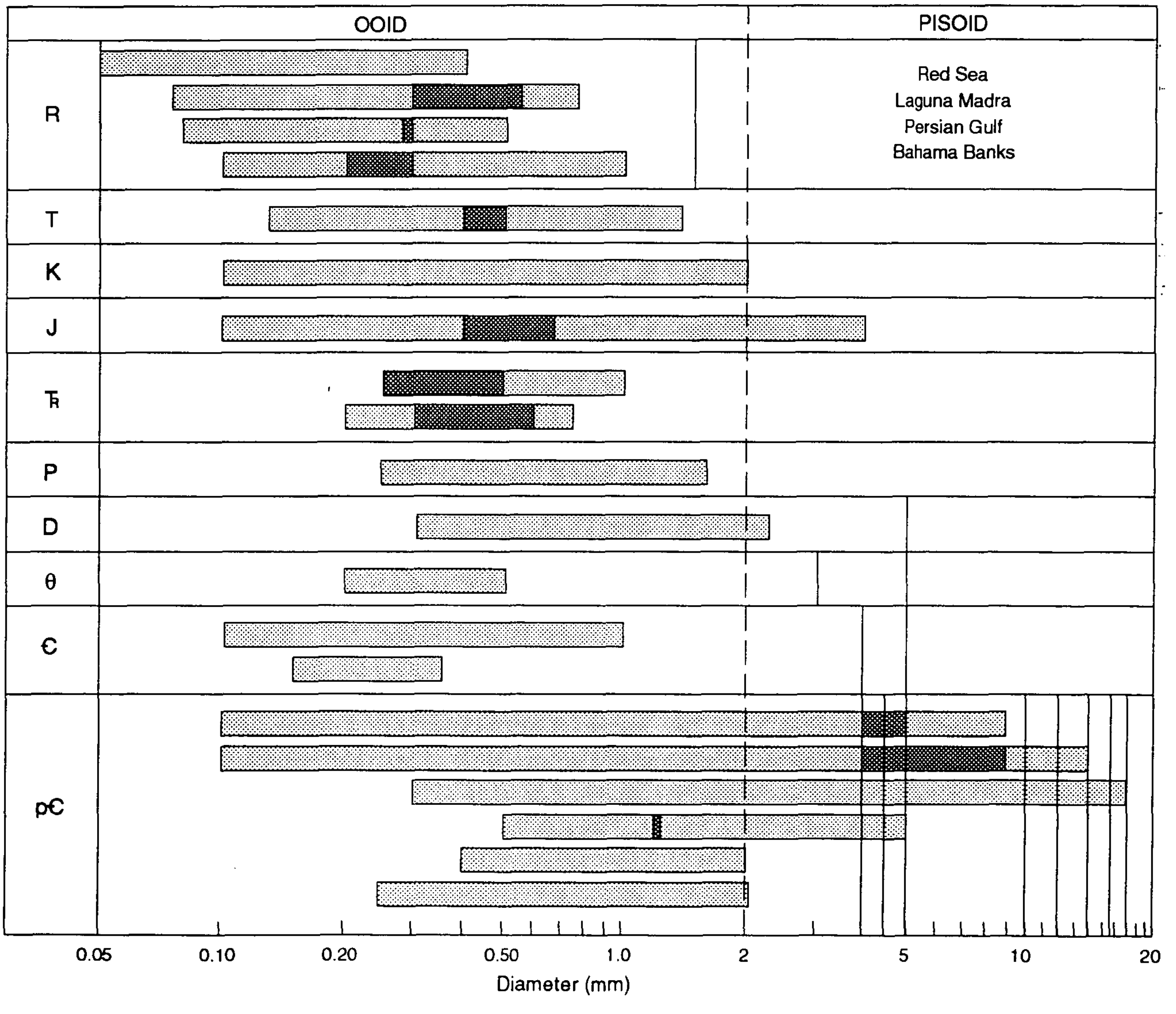
The cements and diagenesis of the ooid grainstones are discussed in Section 1.1.4.6.

Figure 6-3: (a) Size distribution of ooids/pisoids from the Lady Loretta Formation. The bars represent the range of diameters observed in thin section, the darker portion corresponding to one standard deviation from the mean and the median value is marked by a diamond (see text for qualifying remarks). Note that many overlap with, and one sample lies entirely within, the pisoid grainsize. The apparent wide range in diameters between samples and the degree of sorting within samples should be compared to the other Proterozoic examples shown in (b).

(b) A compilation of marine and paralic ooid/pisoid size distribution through time. The bars represent the size ranges reported from each period. The most common sizes, where reported, are shown as darker segments. The diagram is based on Flügel (1982) with additional material from Chadha (1982), Elmore (1983), Hall and Goode (1978), Tucker (1984, 1985), Singh (1987) and Swett and Knoll (1989).The vertical lines at the right represent the maximum ooid/pisoid diameter reported from these and other studies quoted in Sumner and Grotzinger (1993). Proterozoic, particularly Neoproterozoic, coated grains are significantly larger than their Phanerozoic counterparts.



SAMPLE
OOID
PISOID
LLD395
KD4.359
KD4.357B5
KD4.357B2
KD4.357B1
KD4.357A
KD1.352
KD2.308
KD3.304
KD3.279B
POC264
POC257
CCC137A
0.05
0.10
0.20
0.50
1.0
2
5
10
Diameter (mm)



OOID
PISOID
R
Red Sea
Laguna Madra
Persian Gulf
Bahama Banks
T
K
J
Ŧ
P
D
θ
Є
pЄ
0.05
0.10
0.20
0.50
1.0
2
5
10
20
Diameter (mm)

Sample	n	μ	σ	Max	Min	Median	Comments
CCC137A	89	0.40	0.21	1.00	0.09	0.38	no compound forms
POC257	60	1.25	0.12	1.51	0.97	1.26	compound forms excluded
POC264	94	0.57	0.14	0.84	0.24	0.62	no compound forms
KD3.279B	65	0.50	0.16	0.70	0.20	0.54	no compound forms
KD3.304	73	0.61	0.10	0.82	0.32	0.62	smaller are less spherical
KD2.308	56	0.68	0.09	0.82	0.36	0.68	no compound forms
KD1.352	131	1.53	0.30	2.26	0.48	1.51	few compound forms
KD4.357A	55	1.94	0.37	2.61	0.88	1.98	compound forms excluded
KD4.357B1	47	2.91	0.66	3.84	1.54	2.99	compound forms excluded
KD4.357B2	60	5.32	1.29	8.33	2.18	5.47	compound forms excluded
KD4.357B5	94	3.08	0.76	4.35	1.35	3.07	compound forms excluded
KD4.359	46	0.76	0.53	2.37	0.13	0.64	poorly sorted, compound excl.
LLD.395	80	0.38	0.22	0.71	0.11	0.31	bimodal, 0.1-0.2 and 0.5-0.7

Table 6-1: Diameters of chemically precipitated multi-coated grains in the Lady Loretta Formation, expressed in millimetres.

6.4 INTERPRETATION AND DISCUSSION

6.4.1 Formation of Chemically Precipitated Multi-Coated Grains

Chemically precipitated multi-coated grains can form in a variety of environments and by several processes.

Although modern ooids are known from temperate and polar regions, the majority form in the tropics or sub-tropics in high-energy shallow water environments influenced by wave action or strong tidal currents. Conditions that favour the development of ooids in recent shallow marine environments (from Flügel, 1982) include:

- at least occasional, very strong agitation of the water
- very shallow water, generally less than 2 m
- normal or increased salinity, generally above 35.8‰ NaCl (Lees, 1975)
- warm water, generally above 20°C (colder conditions can be compensated by higher salinity - Lees, 1975)
- the presence of algae, bacteria or organic substances
- water supersaturated with carbonate
- a supply of potential nuclei
- few organisms that remove carbonate from the water
- relatively constant environmental factors (duration of growth for "Recent" ooids is 100 to 1000 years).

Multi-coated grains, sometimes superficially similar to marine ooids/pisoids, can form as concretions by chemical precipitation in other environments. Pisoids are formed in terrestrial, lacustrine and vadose-marine settings. Terrestrial environments include caliche, cave pearls and hot spring deposits. Lacustrine pisoids are known from freshwater and salt lakes. Nearshore hypersaline environments and spring-fed supratidal flats are where vadose-marine pisoids are formed (Flügel, 1982; Tucker and Wright, 1990). The pisoids are commonly found beneath emergent tepee structures. Peritidal vadose pisoids are relatively common in the geological record and typically show two distinct phases of growth. An inner evenly-laminated cortex formed as a mobile phase is followed by irregular commonly asymmetric downward-projecting laminae. This gravitational fabric is accompanied by infilled fractures, perched inclusions, and bridge-like structures between adjacent pisoids. Such features are indicative of *in situ* growth (Demicco and Hardie, 1994; Tucker and Wright, 1990).

6.4.2 Marine or Peritidal Vadose?

On the basis of the similarity to modern ooids and the numerous documented ancient examples, the more-abundant ooids less than 1.0 mm d from the Lady Loretta Formation are almost certainly of marine origin. This includes those from the vicinity of the mine.

The unusually large chemically precipitated multi-coated grains are also interpreted as of marine origin. Despite evidence of vadose cementation in some of the Lady Loretta examples (pendant and meniscus cements); the pisoids, themselves, are not interpreted as vadose concretions. They lack the diagnostic features of peritidal vadose concretions described above. The similarity of their morphology to the smaller ooids and to the equally-large compound aggregate grains is substantive proof that the same process was involved. Graded bedding, sorting and intermixing of ooids, pisoids and aggregate grains are all indicative of a sedimentary origin. The stable isotopes are also similar to marine carbonates from elsewhere in the formation (see Section 4.3).

6.4.3 The Significance of Size and Sorting

Modern marine and non-marine chemically precipitated multi-coated grains have a relatively narrow size range compared to detrital clastic particles. The largest modern coated grains have been documented from non-marine environments such as lakes. Unusually large (> 2 mm) chemically precipitated multi-coated grains were described from a pipe carrying freshwater that was leaching grout from dam foundations (Rao and Naqvi, 1983).

The distribution of sizes of marine and paralic chemically precipitated multi-coated grains varies through time. Marine and paralic examples are summarised in Figure 6-3b. Marine ooids greater than about 1.5 mm are not known from Recent sediments (Swett and Knoll, 1989; Sumner and Grotzinger, 1993 and references therein). Most Recent ooids are commonly 0.5 mm or less. Cambrian, and younger, ooids have a broader spectrum of sizes, with values commonly between 0.10 and 2.0 mm. Proterozoic, particularly Neoproterozoic, chemically precipitated multi-coated grains show an extreme range of sizes (up to 17 mm d). Note that many, despite having an identical morphology to true ooids, fall within the pisoid size category.

The larger Lady Loretta examples have a similar maximum size to the "giant ooids" of the Neoproterozoic and can be compared to the work of Chadha (1982), Kidder and Hall (1993), Knoll and Swett (1990), Radwanski and Birkenmajer (1977), Singh (1987), Sumner and Grotzinger (1993) and Zempolich *et al.* (1988). Numerical modeling by Sumner and Grotzinger (1993) tested the relative significance of numerous factors in determining the formation of over-sized ooids. They demonstrated that the four most important factors were:

- low supply of new ooid nuclei
- high cortex growth rate
- high average water velocity
- high velocity gradient.

If these factors were all favourable to produce the unusually large examples from the Lady Loretta Formation, a highly agitated shallow marine carbonate environment close to chemical saturation with little or no detrital clastic input to provide new appropriately sized nuclei is interpreted. Sumner and Grotzinger (1993) concluded that the abundance of "giant ooids" during the Neoproterozoic was due to the prevalence of carbonate ramps over rimmed shelves at that time (the lack of reefal microbialites allowing higher wave energy) and this may also have some relevance to parts of the Lady Loretta Formation (see Section 10.2).

The more conventional-sized ooids from the Lady Loretta Formation overlap in size with Recent examples from both lagoonal and shallow marine environments and similar environments of deposition are envisaged. The bimodal current directions can be interpreted to reflect deposition above wavebase and the large scale cross-stratification implies deposition in shoals. In modern environments, the vast majority of ooids form in waters less than 2 m deep. Newell *et al.* (1960) documented a correlation between the net concentration of Bahamian ooids and water depth as summarised in Table 6-2 (from Flügel, 1982). Modern hypersaline environments such as Laguna Madre typically have less than 30% ooids by volume and contain a high proportion of asymmetric normal, superficial and compound ooids (Flügel, 1982; Freeman, 1962; Rusnak, 1960a). This would suggest that the majority of ooid grainstones from the Lady Loretta Formation formed in water of normal marine salinity less than 7 m deep.

	Percent Volume Ooids	Water Depth (m)
Bahamian Ooids	> 70	0-7
	70-40	2-7
	40-20	2-15
Lady Loretta Fm	> 70	< 7

Table 6-2: The relationship between net concentration of ooids and water depth compared to grainstones from the Lady Loretta Formation. Bahamian data from Newell et al. (1960) and other references in Flügel (1982).

The bimodal distribution of ooid size from the vicinity of the Lady Loretta mine is similar to that described from a number of Recent marginal marine environments. The size range and morphology of the ooids are very similar to those from the Ras Matarma Lagoon, Gulf of Suez (Sass *et al.*, 1972) and a similar shallow, marginal marine, environment is suggested. The reverse grading of ooid grainstones might not reflect increasing energy. Sumner (1995) interpreted such grading as the "result of a single influx of ooid nuclei that were coated and progressively buried as they grew, leaving only larger and larger ooids at the sediment-water interface to continue growing".

6.4.4 Significance of Internal Morphology

Experimental work and studies of modern naturally-occurring ooids have shown that chemically precipitated multi-coated grains can form in both high- and low-energy conditions, but that each will produce a different internal geometry. High energy ooids are characterised by a tangential arrangement of baton like crystals oriented with their long-axes parallel to the cortical laminae. Aragonitic Bahamian ooids are of this type. "Quiet water" ("less-agitated water" might be a better term) ooids/pisoids have a radial fabric, and are formed from supersaturated seawater containing organic matter (Davies *et al.*, 1978; Ferguson *et al.*, 1978; Flügel, 1982). Modern Trucial Coast ooids are examples. Combinations of tangential and radial fabrics within single ooids are known from modern lagoons (Land *et al.*, 1979) and ancient settings (Tucker, 1984). All ooids require at least intermittently agitated water. On the basis of studies of modern ooids from the Bahama Banks, the shallowest water ooids have a relatively small nucleus and numerous laminae in the cortex (Newell *et al.*, 1960; Flügel, 1982).

In almost all examples from the Lady Loretta Formation, the ratio of nucleus to cortex is consistent with a shallow-water origin based on the Bahamian analogy. The radial-tangential fabric, evident as sweeping extinction in thin section, is most like the modern ooids from less-agitated waters. The three-layered morphology of the larger ooids/pisoids from the Lady Loretta Formation resembles Proterozoic examples described by Chadha (1982) and Tucker (1984). Chadha (1982) advocated a Coorong-like setting of ephemeral lagoons or playas. Tucker's (1984) calcitic and two-phase ooids (types (iii), (vi) and (vii) in his Fig. 19) are very similar to the Lady Loretta examples. He drew an analogy with modern ooids in Baffin Bay, Texas, a shallow lagoon that is generally hypersaline, but can be brackish to fresh after storms. These lagoonal interpretations are only partly consistent with the theoretical findings of Sumner and Grotzinger (1993), who suggested a more agitated (and presumably open-water) environment.

6.4.5 Original Mineralogy of the Coated Grains

Recent ooids from marine settings and hypersaline lakes are mostly aragonitic in composition, but such an interpretation is unlikely for the examples from the Lady Loretta Formation. Recent high- and low-magnesian calcite ooids are less common and biminerallic forms occur in lagoons that vary from hypersaline to fresh and in alkaline lakes. Both aragonite and high-magnesian calcite pisoids have been recorded from marginal marine hypersaline environments. Low-magnesian pisoids occur in a variety of non-marine environments (Tucker and Wright, 1990).

Neoproterozoic "giant ooids" (now dolomite) were unanimously interpreted as original aragonite mineralogy. There are far fewer documented examples of unusually large marine chemically precipitated multi-coated grains from the Mesoproterozoic and Palaeoproterozoic. Tucker (1984) described calcitic, aragonitic and mixed calcitic-aragonitic ooids from the Mesoproterozoic Belt Supergroup. Hall and Goode (1978) illustrated pisoids, aggregate grains and giant ooids from the Kulele Creek Limestone of probable Palaeoproterozoic age from the Nabberu Basin in Western Australia. As discussed in Section 4.2, the examples from the Lady Loretta Formation may be the first comprehensively documented over-sized ooids from the Palaeoproterozoic and they may be the first documented examples of such large Proterozoic coated grains that did not have an aragonite precursor.

6.5 SUMMARY

The most common ooids from the Lady Loretta Formation have morphologies in common with modern marine ooids formed in shallow, warm-water, agitated settings. On the basis of this and the sedimentary structures in the grainstone beds, a similar environment of deposition can be interpreted. Ooid shoals probably developed offshore, analogous to sand bars, and possibly in a back-reef setting between the shelf rim and a carbonate lagoon. The presence of ooid grainstone beds in the Upper Clastic Unit some 120 m stratigraphically above the Ore Sequence is good evidence for agitated marine conditions at that time.

The unusually large ooids/pisoids from the western flank of Kamarga Dome are superficially similar to other giant ooids from the Neoproterozoic, but in contrast, the examples from the Lady Loretta Formation are unlikely to have had an aragonite precursor.

Chapter 7 - Storm Deposits

7. STORM DEPOSITS

7.1 INTRODUCTION

Storm deposits have received increased attention in the geological literature over the past few decades and are now recognised to be common in lacustrine, glaciomarine and marine environments (Dyson, 1995a). Modern examples have been studied in their own right since the early 1960s and ancient examples were being widely recognised during the early 1970s. For example, Reineck and Singh (1972) interpreted graded rhythmites of sand/mudstone as storm-generated layers. The term "tempestite" was introduced for ancient storm deposits by Kelling in Ager (1974). Kumar and Sanders (1976) undertook a comprehensive comparison of ancient and modern examples. Recognition of hummocky cross-stratification by Harms *et al.* (1975) led to a surge of publications, including the definition of a distinct storm-generated facies by Hamblin and Walker (1979) and the review by Dott and Bourgeois (1982). More recent literature has focused on shore-parallel geostrophic versus catastrophic flow and the relationship between distal turbidites and tempestites (*e.g.* Nelson, 1982; Einsele and Seilacher, 1991). More reviews of storm deposits are given in Einsele (1982), Einsele *et al.* (1991) and Dyson (1995a).

Storm deposits, in both clastics and carbonates, contain a suite of diagnostic sedimentary structures including hummocky and swaley cross-stratification, quasi-planar lamination, fining-up couplets, scoured gutter casts and imbricated plate breccias (Table 7-1). There is some lithological control on the types of storm deposits produced because of the different substrates involved and it should be noted that many of the individual features described from storm deposits can also occur in tidal deposits (*e.g.* flaser and wavy bedding, parallel bedded graded rhythmites) or distal turbidites (*e.g.* climbing ripples, settling couplets). Indeed, one might expect a gradation from one to another since storms will enhance tidal currents and the sediment suspension generated by storms will be effectively the same as that produced by a gravity-flow turbidity current (see Dyson, 1995a and references therein for discussion).

The following sections describe the deposits diagnostic of storm activity that have been identified in the Lady Loretta Formation.

7.2 STORM BEDS

7.2.1 Terminology and Description from Literature

Several types of fining-up bedforms are taken to be indicative of storm deposits. A plethora of names have been applied to these storm beds and some authors accept the term to be synonymous with "tempestite", while others argue that the other storm facies described in this Chapter (such as plate breccias) are also tempestites. The present study follows Tucker and Wright (1990) and much of the description below is taken from them.

Proximal	%	Distal	%
quasi-parallel lamination / horizontal planar lamination	82	distal Bouma sequences	14
fining-up couplets / rhythmites	77	fining-up couplets / rhythmites	82
crossbedding (undifferentiated)	32	crossbedding (undifferentiated)	55
swaley cross-stratification	14	swaley cross-stratification	9
hummocky cross-stratification	64	micro-hummocky cross-stratification	14
flaser / wavy bedding / mud drapes	50	flaser / wavy bedding / mud drapes	64
wave ripples	64	wave reworked ripple tops	9
current ripples	23	current ripples	14
combined flow / interference ripples	18	combined flow / interference ripples	18
climbing ripples	36	climbing ripples	55
basal scours	95	basal scours	86
flute / gutter / pot casts / sole marks	59	flute / gutter / pot casts / sole marks	32
load casts	27	load casts / convolute bedding	77
plate breccias	23	plate breccias	9
coquinas / bioclastic deposits	32	geopetal structures	5

Table 7-1: A list of sedimentary structures common in storm deposits (from Dyson 1995a). The percentages are a crude estimate of the abundance of each feature reported in the literature based on a survey of 22 references by the author.

Part of the problem in characterising storm beds is their variability. They grade from amalgamated sandy sequences (with hummocky cross-stratification) through to centimetre-thick graded units within mudstones that mimic Bouma sequences in turbidite deposits (Nelson, 1982). Another problem is that there have been very few studies of carbonate tempestites in rocks that pre-date metazoans (no bioclastic debris other than microbial mat).

Despite these restrictions, there are some unifying features for both clastic and carbonate sequences. The base of storm beds is always sharp and erosional and a variety of sole structures (including the pot and gutter casts described in Section 7.5) occur. Graded bedding is another common feature and a basal lag is sometimes present. Flat bedding and various types of crossbedding occur within storm beds, and commonly a sequence of structures reflecting waning flow is seen. Flat-bedding with parting lineation (quasi-planar lamination) passing up to ripple cross-lamination would be an example. The tops of storm beds are commonly rippled, with symmetrical wave-generated forms or current ripples. Other storm beds have gradational upper boundaries (Tucker and Wright, 1990).

Storm beds typically show marked changes in character with increasing distance from the shoreline and increasing water depth. Proximal storm beds are relatively thickly bedded, bioclast-dominated (at least in the Phanerozoic) and coarse-grained, with many composite and amalgamated beds. Distal equivalents are mud-dominated (either clastic or carbonate) and thinner, single-event, deposits. This pattern is a function of decreasing strength of storm waves and currents away from the shoreline. The continuum between proximal and distal is complicated by shelf geometry, topography and variations in the strength, frequency and focus of storms (Tucker and Wright, 1990). Despite these complications, there have been numerous attempts; Dyson (1995a) lists ten between 1975 and 1986; to generate an idealised facies sequence for tempestites. Most of the recent models are based on Allen (1984), Dott and Bourgeois (1982), Walker *et al.* (1983) or Walker and Plint (1992).

7.2.2 Examples from the Lady Loretta Formation

The Lady Loretta Formation contains numerous examples of thin, graded beds with erosional bases. Those in the carbonate-dominated facies in the north commonly contain the characteristic upward transition from quasi-planar lamination to ripple cross-lamination and it is possible to demonstrate that they grade laterally to imbricated plate breccias locally. Mixed carbonate/siliciclastic examples occur sporadically in the core from drillhole Amoco 83-5. The argillaceous facies in the south, and in particular from the vicinity of the Lady Loretta mine, contain numerous thin fining-up beds with erosional bases. Typically, these have a fine to very fine grained sandstone at the base and are capped by laminated argillaceous siltstone or shale. In rare examples, ripples are present towards the top.

7.2.3 Interpretation

The examples from the north that are associated with imbricated plate breccias can be confidently interpreted as storm deposits as described by other workers. However, in the argillaceous facies it is very difficult to distinguish between tidal rhythmites, true turbidites (*i.e.* gravity flows) and settling from suspension generated by storms. The distinguishing features of tidal rhythmites are discussed in Section 5.4 and by Greb and Archer (1995). The distinction between turbidites and tempestites has often been based on the assumption that tempestites will have bidirectional, and proportionally fewer, flute casts. This has been contested by several workers (*e.g.* Swift *et al.*, 1987) and is discussed in Dyson (1995a). It becomes academic in the argillaceous facies of the Lady Loretta Formation where there are few flute casts in outcrop and all core is unoriented. Potentially then, many of the thin-bedded graded units in the Lady Loretta Formation are unrecognised distal storm beds.

7.3 HUMMOCKY AND SWALEY CROSS-STRATIFICATION

7.3.1 Description from Literature

Hummocky and swaley cross-stratification are well documented in the geological literature. Detailed descriptions of the characteristic internal geometry are given in Cheel and Leckie (1993), Dott and Bourgeois (1982) and Dyson (1995a,b). However, as pointed out by Demicco and Hardie (1994), the original definitions of these bedforms have been so modified and misquoted that illustrations in current sedimentology textbooks bear little resemblance to the originally defined sedimentary structures.

As now generally accepted, hummocky cross-stratification typically occurs in sharp-based very fine to fine grained sandstone (5-100 cm thick) interbedded with bioturbated mudstone, or in amalgamated sandstone beds several metres thick. Tucker and Wright (1990) described the carbonate and mixed carbonate/siliciclastic equivalents. Thin and discontinuous gently curving laminae and low-angle cross-lamination with dips of less than 10-15° are either convex-up (a hummock) or concave-up (a swale). The laminae commonly intersect at low angles and thicken towards the centres of both swales and hummocks. The intersections between laminae vary from erosional truncations to non-erosional downlap. Hummocks are generally circular and radially symmetrical in plan, typically a few tens of centimetres high, with a lateral spacing of 1 to 6 m and are commonly mantled with wave-formed ripples (Dyson, 1995a; Tucker and Wright, 1990).

The term swaley (also spelt swaly) cross-stratification was introduced during the 1980s to distinguish a variant of hummocky cross-stratification in which swales were preserved preferentially and hummocks were rare or absent. In contrast to the random dip orientation in hummocky cross-stratification, some swaley cross-stratification shows consistent directional dips. Swaley cross-stratification has been reported commonly from <2 m thick beds of fine to medium grained sandstone that do not show evidence of amalgamation (Dyson, 1995a).

7.3.2 Examples from the Lady Loretta Formation

Both hummocky and swaley cross-stratification occur in the Lady Loretta Formation, but neither is abundant. Several poorly-preserved examples of hummocky cross-stratification occur near the Redie Creek and Russell Creek sections and another possible example occurs north of the Thornton River type section. All are in silty, fine to medium grained sandstones, although the examples from Redie Creek were probably originally variably dolomitic. Only a single example of swaley cross-stratification was identified. It occurs in fine grained sandstone that is discontinuous along strike in an otherwise shale-dominated area between KD4 and KD5 sections at Kamarga Dome.

7.3.3 Interpretation

Hummocky and swaley cross-stratification are unanimously interpreted as storm deposits. However, the combination of processes involved in their formation have been the subject of debate for over 15 years (see discussion in Dyson, 1995a). The relative roles of wave-generated oscillatory or combined flow produced by the passage of storms and ebb tidal currents remain ambiguous.

In spite of this difficulty in precisely defining the processes involved, hummocky and swaley cross-stratification appear to be useful palaeo-environmental indicators and are taken to be diagnostic of inner shelf storm deposits, between fairweather and storm wavebases, where fairweather reworking is minimal and therefore where their preservation potential is greatest (Hamblin and Walker, 1979). Duke (1985) examined the palaeogeographic distribution of over 100 examples ranging from Proterozoic to Recent and concluded that tropical hurricanes and intense winter storms are the only types of storm capable of producing hummocky cross-stratification.

The examples from the Lady Loretta Formation, through few in number, corroborate other evidence of storm deposits and can be interpreted to indicate water depths between fair- weather and storm wavebases. The relative lack of these features in contrast to the abundance of other types of storm deposit (described below) has been noted from other Palaeoproterozoic formations (*e.g.* McCormick and Grotzinger, 1993). This may be because:

- hummocky and swaley cross-stratification are not be preserved
- the argillaceous and carbonate grainsizes are not conducive to the formation of large amplitude bedform storm deposits
- the carbonate substrate is cemented early or microbially-bound and is ripped up as plates (see following section)
- the facies are predominantly above fairweather wave base, indicating broad shelves
- lack of wave fetch
- microbial "reefs" baffle onshore-directed storm energy.

7.4 IMBRICATED PLATE BRECCIAS

7.4.1 Description

Plate breccia is also referred to as rip-up plate, flake, mud-chip, flat pebble, imbricate intraclast, sharpstone or edgewise breccia or conglomerate. As the various names imply, it consists of a closed framework of angular to sub-rounded, flat to slightly curled plates, in beds typically 3 cm to 1 m thick. The plates are commonly imbricated, often into a swirled pattern in plan, and are generally composed of carbonate mudstone, sometimes with a laminated microbial fabric. They rarely show evidence of plastic deformation. Care must be taken to differentiate true sedimentary plate breccias from similar structures produced by pull-apart or soft sediment deformation disrupting thin beds. These "pseudo-breccias" commonly have a stoped roof (see Demicco and Hardie, 1994). Both true sedimentary plate breccias and pseudo-breccias occur in core of the Lady Loretta Formation from drillhole Amoco 83-5.

Plate breccias are abundant and widespread in the Lady Loretta Formation (and other formations in the McNamara Group). They are ubiquitous in all outcrop sections north of the Lady Loretta mine and are also common in core. Good examples occur in the Tom Cat area, a few kilometres northeast of the mine. Beds of imbricated plate breccia commonly persist along strike for hundreds of metres and tend to occur sporadically at the same lithostratigraphic level (Figure 7-1).

Typical examples (Figures 7-2a,c) show several characteristic features. The clasts are not regularly spaced and packing of clasts varies from very tight to open within any single bed. As shown in Figure 7-2a, the basal portion commonly contains larger and thicker plates up to 20 cm across and less than 1 cm thick but, overall, the unit is not graded. Most plates are about 6 cm across and 0.5 cm thick and consist of laminated or thin bedded dolostone and/or silty dolostone. Microbial fabrics can be identified in some plates, but there appears to be proportionally fewer than in the "stromaclast" examples described by Sami and James (1994). In section, the plates are commonly imbricated in opposed directions (evident in both Figures 7-2 a and c). The domains defined by consistent clast orientation in section are not stratigraphically concordant and in some examples appear to thicken consistently in one direction (to NW at Kamarga Dome). In plan view, imbrication commonly defines swirled patterns up to several metres across that grade into one another. This is similar to other Proterozoic examples described by Fairchild and Herrington (1989). The polygonal plan view described by Demicco and Hardie (1994) was not obvious. The base of the bed can be concordant (Figure 7-2a) or erosional with up to 10 cm of relief locally. In extreme cases, flake pockets form (see Section 7.5).

The matrix to the breccia varies from finely to coarsely (re-)crystalline dolomite. Clasts, or both clasts and matrix, are silicified in outcrop. The rare examples of primary carbonate cements identified were cavity-fill in shelter porosity beneath plates. The tops of the beds show infiltration by the overlying sediment. In rare examples, small domal microbialites colonised the up-turned edges of the plates. Beds range in thickness from about 3 cm to a maximum observed of 85 cm. The beds vary considerably in thickness down dip but it was not possible to quantify changes in bed thickness down dip or along strike. It is possible to trace some beds along strike into graded carbonates consisting of quasi-planar lamination passing up to cross-lamination and ripples. Such a relationship was illustrated from elsewhere by Tucker and Wright (1990) in their Figure 4.12. There is a crude relationship between maximum clast size and bed thickness as observed in other examples by Lee and Kim (1992).

7.4.2 Interpretation

Plate breccias can form from different processes in several settings:

- subtidal to intertidal storm deposits
- in the high intertidal or supratidal zone as a result of desiccation
- by the discharge of groundwaters in the supratidal zone, in which case they are evidence of non-marine hydrological conditions.

Modern examples produced by storms have confirmed that plate breccias can be deposited almost instantaneously on supratidal levées and the lee side of beach ridges (Sepkoski, 1982). They are also known to occur in modern hypersaline environments, supratidal flats and as strandline deposits on the edges of tidal channels and on muddy beach ridges (Demicco and Hardie, 1994; Sepkoski, 1982). In these cases, the plates were sourced from the supratidal zone, where case-hardened mud-cracked sediments were reworked by spring or storm tides. In contrast, in Hamelin Basin, offshore Shark Bay WA, plate breccias form sheets in the sublittoral zone and were sourced subaqueously from hardgrounds (Hagan and Logan, 1975).

Figure 7-1: Distribution of plate breccias and gutter casts in the Lady Loretta Formation.

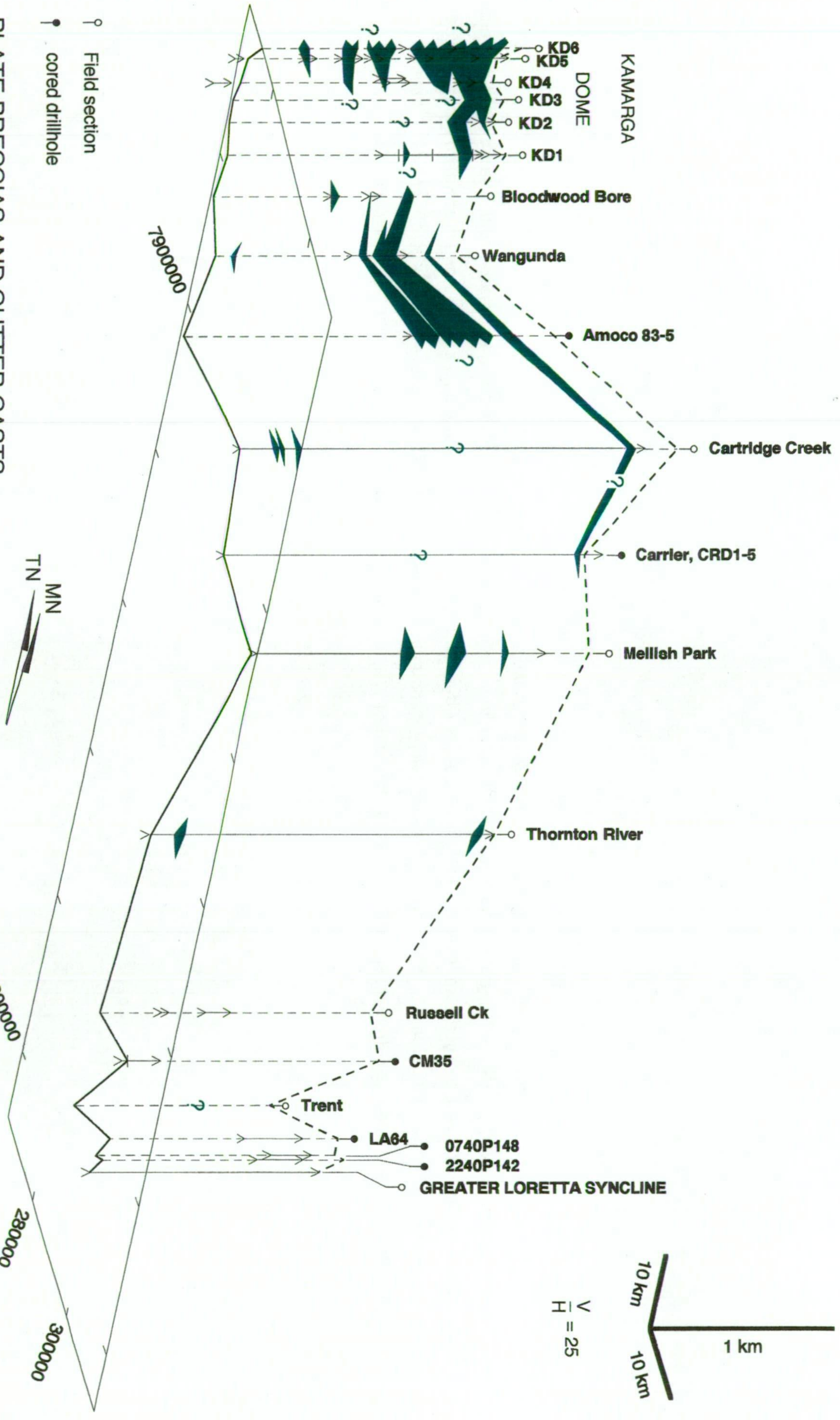


PLATE BRECCIAS AND GUTTER CASTS

Figure 7-2: Plate breccias and gutter casts. (a) Imbricated plate breccia from Wangunda. Note the larger clasts at the base and the opposed directions of imbrication in section. (b) A series of erosively-based conglomeratic gutter casts (flake pockets) seen in section, Kamarga Dome. The thinner and broader examples at the base of the photo extend for about 75 m laterally. Note the deeply scoured bi-lobed channel in the centre of the photo and the isolated rounded channel at the top. (c) Imbricated plate breccia in core from Amoco 83-5, 31.5 m. Note the opposed imbrication directions and that some of the darker plates consist of microbial mat. Coin is 3 cm d and bar scale is 1 cm.

The more abundant ancient examples are also assigned a wide provenance. Some early workers (*e.g.* Braun and Freidman, 1967; Wilson, 1975) used them as indicators of intertidal deposition. Sepkoski (1982) and Lee and Kim (1992) argued that examples not associated with stromatolites, desiccation cracks, birds-eye fenestrae or tidal bedding were probably subtidal hardgrounds ripped-up by storms. They interpreted examples to thicken into shallower water. Cambrian examples described by Wisonant (1987) and Mount and Kidder (1993) were also attributed to the storm erosion of subtidal, sub-fairweather wavebase substrates with some post-storm reworking by tidal currents. Sami and James (1994) noted a strong association between "stromaclast" breccias and wavy microbialite on a Palaeoproterozoic low- to moderate-energy lower intertidal to shallow subtidal seafloor and interpreted the breccias as storm deposits. The lateral gradation to a typical graded sandstone/argillite storm bed (as illustrated by Tucker and Wright, 1990) is also diagnostic of a storm origin for the plate breccias and discounts the possibility of them being a transgressive lag deposit.

The relative abundance of plate breccias during the Proterozoic and Cambrian may be due to several factors. The lack of intertidal and subtidal burrowing organisms would have enabled early cementation of the substrate which was then ripped up as plates. Alternatively, perhaps high intensity storms were more frequent. Other authors have argued that the prevalence of plate breccias can be attributed to the relative abundance of microbially-bound material.

The plate breccias in the Lady Loretta Formation were originally interpreted as beach or tidal channel deposits by Sweet and Hutton (1980), who believed that the clasts were produced by subaerial exposure. In contrast, and in accord with the current consensus, plate breccias from the Lady Loretta Formation have been interpreted as shallow subtidal to intertidal deposits resulting from wave action and surge generated by storms. Their abundance, lateral extent, lateral facies equivalents and internal textures are not consistent with a desiccation or groundwater-discharge origin. The opposed imbrication directions and swirled arrangement in plan are interpreted to indicate oscillatory and vortex flow as produced by storms and are not consistent with the "pseudo-imbrication" on large-scale foresets or the polygonal plan-view described by Demicco and Hardie (1994) from desiccation-derived breccias. Since the majority of clasts are not microbial, sub-marine hardgrounds are implicated as the most common source of plates. The fact that some domains of imbricated clasts thicken to the NW may be a vector toward shallower water, at least locally.

7.5 GUTTER AND POT CASTS

7.5.1 Terminology and Description

Gutter and pot casts are the in-fill of small erosional depressions and channels. As the names imply, gutter casts are elongate and pot casts are rounded, non-linear, features. These sedimentary structures, as described by Myrow (1992b) and Jennette and Pryor (1993), are distinct from scour pits or wash-out rills which typically do not have in-fill preserved in outcrop. Previous workers have used different terminology to describe gutter and pot casts (*e.g.* the "flake pockets" of Fairchild (1980)). Myrow (1992b) developed a descriptive system of nomenclature for pot and gutter casts concentrating on shape, lateral continuity and infill. The same terminology will be used here.

Hundreds of examples of gutter and pot casts were observed in the northern outcrops of the Lady Loretta Formation. Gutter casts are far more common than pot casts. Although not laterally continuous, they are commonly locally closely-spaced and occur at discrete stratigraphic intervals. In carbonate and mixed carbonate/siliciclastic facies, they are best exposed in cross-section on benched outcrops. Elsewhere in carbonate-dominated facies, the casts are preferentially silicified and preserved in positive relief after the surrounding bed has been weathered away. In cross-section, the casts range between 5-55 cm in width and 2-12 cm deep. Cross-section profiles range from deep-rounded, shallow-rounded, bi-lobed (Figure 7-2b) to irregular. The majority of the gutter casts are several metres long and range from slightly sinusoidal to almost straight. The measured trends of the channel axes are included in the palaeocurrent analysis in Section 5.5. The gutter casts commonly deepen in one direction and vary from discrete subparallel structures to connected thick beds. In the latter case, the capping bed spreads over several basal scours each less than the thickness of the connecting bed. The infill generally reflects lateral, presumably basinward, lithological associations.

Figure 7-2b illustrates an example from dolomitic lithologies at Kamarga Dome where the matrix to the gutter-fill is a silty dolostone with a clast-supported framework of dolostone plates very similar to those in nearby imbricated plate breccias. The plates in the gutter casts are most commonly prone (as in Figure 7-2b) but imbricated and swirled examples were also observed at Kamarga Dome. These examples would be described as "conglomeratic" gutter-fill using Myrow's (1992b) classification and are identical to "flake pockets" documented by Fairchild (1980). Rarely, the channel has not been completely filled all the way along its length. The projecting lip and the irregular top produced by upturned plates has affected subsequent deposition.

In the arenaceous and argillaceous lithologies of the Lady Loretta Formation, the infill is most commonly cross-laminated sandstone. Opposed ripple cross-lamination was noted in one example. Angular dolostone clasts are also present in some of the sandstone fills.

7.5.2 Interpretation

Modern examples of gutter and pot casts can form in a variety of ways and in different environments. They may also resemble lateral accretion lags in small tidal channels. However, Jennette and Pryor (1993) and Myrow (1992b) considered that many closely spaced and parallel-aligned gutter casts that project downward from a single bedding surface were diagnostic of storm deposits in a nearshore marine environment.

Their formation involves two distinct phases; erosion and rapid deposition; that occur during a single storm event. In the case of gutter casts, the sometimes steep sides of the channel indicate that the substrate was cohesive. The parallelism of gutter casts is interpreted to indicate that erosion took place under strong offshore-directed unidirectional flow (storm surge or other relaxation flow). Deposition was almost instantaneous and characterised by oscillatory flow, as evidenced by opposed ripple cross-lamination and the variable imbrication of clasts. Pot casts formed by a similar process during vortex flow (Myrow, 1992b).

Using the model developed by Walker and Plint (1992), gutter casts and mudstone intraclasts are more likely to be formed and preserved during shoreface progradation and forced regression of wave- and storm-dominated shorelines. McCormick and Grotzinger (1993) attributed gutter casts in another Palaeoproterozoic formation to a shallower setting than that predicted by the Dott and Bourgeois (1982) model. They suggested that gutter casts might be more common than hummocky/ swaley cross-stratification on fine-grained storm-dominated shelves.

The examples from the Lady Loretta Formation that contain clast-supported carbonate plates are interpreted to have formed as storm deposits in a similar manner to the imbricated plate breccias. They may be a more-erosive lateral equivalent. The same rapid erosion, and filling, of channels in clastic lithologies is also taken as indicative of storm deposits in the shallow subtidal to intertidal zone. These features are most likely to have been preserved during an overall regression.

7.6 SUMMARY

As with several other formations in the McNamara Group, the Lady Loretta Formation contains abundant erosionally-based beds deposited almost instantaneously by storms. Hummocky and swaley cross-stratification, quasi-planar lamination, fining-up couplets, scoured gutter casts and imbricated plate breccias are all present. Several of these are diagnostic of specific environments ranging from lower intertidal to subtidal and between fairweather and storm wavebases. The abundance of plate breccias and gutter casts contrasts strongly to the dearth of hummocky and swaley cross-stratification. The presence of hummocky cross-stratification is interpreted to indicate high-intensity storms and is consistent with a low latitude (tropical) setting.

Chapter 8 - Microbialites

8. MICROBIALITES

8.1 TERMINOLOGY AND THE USE OF MICROBIALITES AS PALAEO-ENVIRONMENTAL INDICATORS

Microbialites, as defined by Burne and Moore (1987), are organo-sedimentary structures, lacking skeletal elements, formed by the interaction between a benthic microbial community and the environment. As used herein, this term includes stromatolites with synoptic relief, thrombolites and prone microbial mats. The various types of microbialite can be classified into morphological groups using the terminology of Walter *et al.* (1992) and have been named in a similar way to Grotzinger (1989) and Sami and James (1993, 1994). These various morphologies may, in themselves, form laterally extensive marker horizons (as in the Esperanza Formation). Alternatively, they can grade vertically and laterally from one to another to constitute "multi-species" mounds and build-ups termed bioherms and biostromes. The present study uses the term "biostrome" in the same sense as Walter *et al.* (1992) (see Demicco and Hardie, 1994 for an alternative definition).

Linnean nomenclature is used here only for a few forms where they are already commonly referred to in the geological literature by their group or genus name. The majority of the microbialites described in this thesis have not been studied in sufficient detail to enable the use of formal taxonomy. Indeed, many are probably undescribed new species.

Used in isolation, most microbial fabrics are not good palaeoenvironmental indicators. Only columnar conical and microdigitate (tufa) forms appear to be reliable indicators of sub-wavebase and peritidal conditions respectively. Certain microbialites are commonly shown as occupying a distinct zone within the platform or shelf (*e.g.* Grotzinger, 1989; Sami and James, 1993, 1994) but these inferences are supported by other sedimentological evidence and facies architecture, as are the interpretations discussed below (see Chapter 10).

The morphological groups recognised from the Lady Loretta Formation are shown diagrammatically in Figure 8-1. The salient features of the microbialites are summarised in Table 8-1.

8.2 PREVIOUS STUDIES

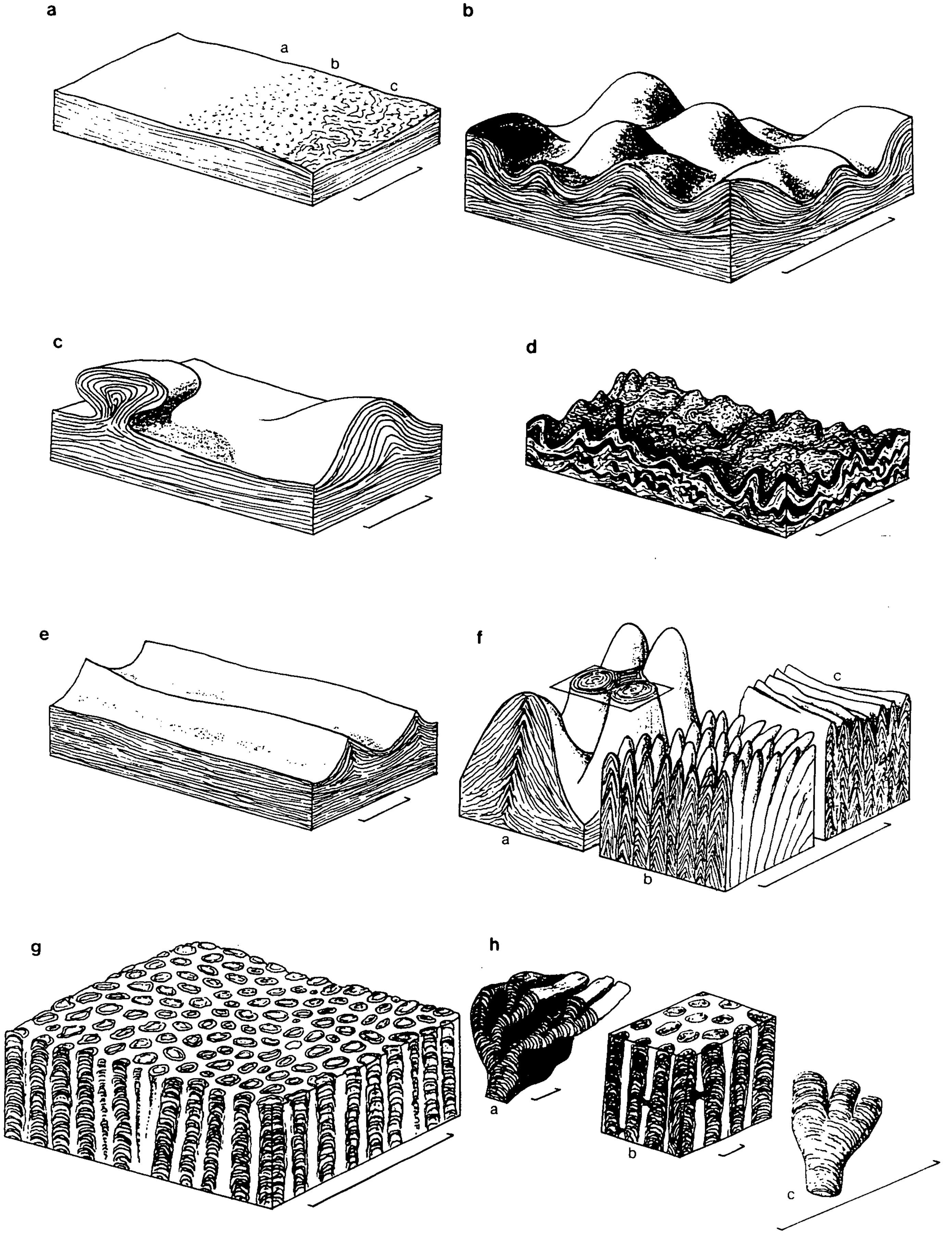
Some of these microbial forms had previously been mentioned in the explanatory notes covering the 1:100 000 scale regional mapping and exploration company reports and will be discussed below.

Blake (1987), Hutton and Wilson (1984) and Sweet and Hutton (1982) described some of the larger microbialites from the Lady Loretta Formation on the Mount Oxide and Mammoth Mines sheets respectively.

Amade (1986) illustrated a domal bioherm supposedly from the Lady Loretta Formation, but this sample may actually occur in the Esperanza Formation.

The first recognition of microbial fabrics at Lady Loretta mine is probably

Figure 8-1: Microbialites from the Lady Loretta Formation. (a) Prone microbial laminite. Smooth, pustular and crenulated surface textures are indicated (a-c). Scale is 10 cm. (b) Linked domal microbialite. Scale is 1 m. (c) Unlinked domal microbialite. A cumulate form is shown on the left and a domal form on the right. Scale is 5 cm. (d) Undulatory domal microbialite showing the alternation of thick dark microbial bands and lighter coloured pyritic material and silicified bands. Scale is 10 cm. (e) Cuspate microbialite. Scale is 10 cm. (f) Various forms of columnar conical microbialite. (fa) shows the larger type in vertical section and partial horizontal section. Note the development of star shaped microbial lamination between the columns. (fb) shows smaller diameter forms locally called 'organpipe stromatolites'. Note the sharply convex laminae in section and the well-defined axial zone. Inclined forms are also illustrated (fc) shows how the same type of microbialite can be elongate in plan view. Scale is 1 m. (g) Pillared columnar microbialite also commonly called 'organpipe stromatolites'. Note the wider spacing of the columns, the absence of an axial zone and the lower relief of the laminae in comparison to the previous example. Scale is 1 m. (h) Macro- and minidigitate columnar microbialite. (ha) illustrates swelling and branching of columns and elongation in plan. (hb) shows nearly parallel columns with bridges. (hc) minidigitate columnar microbialite. Scales in (h) are 1 cm. All drawings are composites based on numerous photos and field sketches.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TYPE	PLAN OUTLINE	LINKAGE	SPACING	ATTITUDE	LAMINAE PROFILE	SYNOPTIC RELIEF	VERTICAL INHERITANCE	LATERAL CONTINUITY	ASSOCIATION	MODE OF OCCURRENCE	DIAGENESIS	DIAMETER TYP., MAX
1. PRONE MICROBIAL LAMINITE	flat	linked	contiguous	prone	smooth, crenulated, blistered	very low	low to moderate	generally high	2,3,4,6,9	tabular biostrome	pyritised, silicified	N/A
2. LINKED DOMAL MICROBIALITE	circular, lobate to elongate	linked	variable	mostly erect	gently convex, hemispherical to bulbous	highly variable	high	variable	1,5,7,8	biostrome, domed bioherm	silicified, rare pyritic	75 cm, 4m
3. UNLINKED DOMAL MICROBIALITE	circular, lobate to scutate	unlinked	isolated	erect	convex, cumulate to turbinate	generally low	low	low to moderate	1	bioherm, intertonguing	pyritised, silicified	6 cm, 10 cm
4. UNDULATORY DOMAL MICROBIALITE	irregular	linked	contiguous	variable	wavy to wrinkled	low	low	moderate to high	1	low relief dome, tabular biostrome	silicified, assoc. pyrite	N/A
5. COLUMNAR CONICAL MICROBIALITE	circular, star-shaped, rarely elongate	mostly linked	contiguous to close	erect to inclined	parabolic, gently to steeply conical	very high	high to very high	high to very high	2,7	tabular biostrome	mostly silicified	12 cm, 45 cm
6. CUSPATE MICROBIALITE	circular to rarely strongly elongate	unlinked, linked widely spaced	isolated	mostly erect	steeply conical to cuspate	moderate	low	low	1,2,3	bioherm	pyritised, silicified	10 cm, 50 cm
7. PILLARED COLUMNAR MICROBIALITE	circular to slightly elongate	unlinked to partly linked	very close	erect to inclined	variably convex to rectangular	moderate to high	moderate to high	generally high but variable	2,5,8	bioherm	some silicified	5 cm, 12 cm
8. MACRODIGITATE COLUMNAR MICROBIALITE	circular, rarely highly elongate	unlinked	close to very close	erect to inclined	rectangular to convex	moderate	moderate	low	2,7	domed and tabular bioherm	mostly silicified	<1-3 cm, 4 cm
9. MINIDIGITATE COLUMNAR MICROBIALITE	highly elongate	unlinked	very close	inclined, recumbent to erect	mostly convex	low to very low	?low	?low	1	?intertonguing	pyritised, silicified	1-2 mm

Table 8-1: Summary of microbial attributes. Those microbialites that commonly occur together are shown in the association column and refer to the numbers shown in the lefthand column.

attributable to Russell *et al.* (1976) who described "a black doubtfully stromatolitic chert (that) immediately overlies ore grade mineralisation" in drillhole 1540P68 (the only significant mineralisation in the Big Syncline). Unfortunately, this core was destroyed. Carr (1981) mentioned "algal structures" from two drillholes in the Small Syncline (2420P121, 593 m; 2480P128, 477-479 m). These drillholes are now believed to have intersected the Esperanza Formation beneath the Carlton Fault Zone and the microbialites are assigned to that formation. The impetus for further study came with the recognition of digitate microbialites intimately associated with the ore and the theory that much of the layered pyrite originally might have been microbial mat (McGoldrick, 1993; McGoldrick *et al.*, 1996*; Dunster, 1996*).

8.3 PRONE MICROBIAL LAMINITE

8.3.1 Description

Prone microbial laminite (or "cryptmicrobial laminite" *sensu* Demicco and Hardie, 1994) can be difficult to recognise, both in the field and in drillcore. Sub-millimetre alternation of organic-rich layers and carbonate cement, and lateral or vertical gradation to more obvious microbial fabrics allows identification of a finely laminated rock as prone microbial laminite. Such textures are commonly laterally extensive. The surface may be smooth, pustular or crenulated (Figure 8-1a). Both silicified and pyritised examples have been documented from the Lady Loretta Formation. Silicified examples commonly grade to domal microbialite and are locally extensive in the lower Lady Loretta Formation and Esperanza Formation, including the area immediately north of the Carlton Fault Zone at the Lady Loretta mine. Figures 8-2a,b show silicified prone microbialite from outcrop of the Ore Sequence Equivalent in the Small Syncline. Pyritised mat (Figure 8-2c), is abundant within the Pyritic Unit, Ore Sequence and Cyclic Unit at the deposit. These examples are similar to those described from elsewhere by Schieber (1986 *et seq.*). Pyritised prone microbialite also occurs associated with other forms of microbialite at Brenda Creek, Carrier, Mellish Park, and Trent.

8.3.2 Interpretation

Prone microbial laminite is not diagnostic of any depositional environment. Similar stratiform microbialites are interpreted to form in deep, quiet water and low energy peritidal environments (Serebryakov, 1976). Modern examples occur in freshwater and saline lakes, in subtidal to high intertidal (Bauld, 1981) and deep marine settings (Williams and Reimers, 1983). Horodyski and Bloeser (1977) described modern prone laminites from the lagoonal Laguna Mormona in Mexico.

On the basis of sedimentological evidence, examples from the Lady Loretta Formation appear to be best developed in quiet water lagoonal and sub-wavebase environments. Other examples associated with an evaporite overprint may have grown on the tidal flats.

8.4 LINKED DOMAL MICROBIALITE

8.4.1 Description

Laterally linked domes are the largest and most conspicuous form of microbialite in the Lady Loretta Formation and are also common in the Esperanza Formation (Figures 8-1b, 8-2e). Domes are typically about 75 cm in diameter with vertical to horizontal aspect ratios of <0.5. Linked domes commonly develop on prone microbial laminite and grade up to columnar or pillared forms. Almost all examples from outcrop are silicified to some extent. Rare poorly preserved pyritised domes up to 50 cm diameter with a synoptic relief of about 20 cm occur in outcrop of the Ore Sequence Equivalent on the eastern limb of the Big Syncline.

8.4.2 Interpretation

By virtue of their sedimentary facies associations (*e.g.* plate breccias), the majority of the larger laterally linked domal microbialites in the Lady Loretta Formation are interpreted as having grown near, or above, wavebase. The smaller forms may have grown in quieter water, lagoonal, conditions.

8.5 UNLINKED DOMAL MICROBIALITE

8.5.1 Description

Unlinked domal microbialites are generally smaller than their linked counterparts by a factor of ten and usually have higher aspect ratios (Figures 8-1c, 8-2f). They commonly occur as isolated thin beds or in association with prone microbial laminites and are mostly preserved as chert. Rare pyritic cumulate forms, 4-6 cm across, occur in outcrop of the equivalent of the Ore Sequence in the Small Syncline (Figure 8-2d). Similar, but silicified, cumulate forms are common at Redie Creek.

8.5.2 Interpretation

A shallow subtidal to lower intertidal or lagoonal environment of deposition is interpreted from the low synoptic relief and the sedimentary facies associations.

8.6 UNDULATORY DOMAL MICROBIALITE

8.6.1 Description

This unusual microbialite is characterised by laterally contiguous microbial sheets separated by laminated chert, chert filling highly-irregularly shaped cavities, bedded pyrite and shale (Figures 8-1d, 8-3a-e). On a small scale, the microbialites range from almost flat, through columnar-layered to pseudocolumnar and domal but are commonly highly contorted. They are arranged into very low relief domal or tabular biostromes. This type of microbialite has unusually high TOC concentrated into relatively thick dark carbonaceous layers and is invariably associated with evaporites and desiccation features. Indeed some of the mat itself appears to have been desiccated, producing curled plates (Figure 8-3e). The undulatory domal microbialites are commonly associated with other high TOC

Figure 8-2: Prone microbial laminites and low relief forms. (a) and (b) Silicified prone microbial laminite, outcrop of Ore Sequence Equivalent, Small Syncline. (c) Ferruginised and silicified pyritic prone microbialite from outcrop of the Ore Sequence Equivalent, sample LLD37. (d) Vertical section of cumulate unlinked domal microbialite, outcrop in Small Syncline. (e) Linked domal microbialite near contact of Esperanza and Lady Loretta Formations, Kamarga Dome. (f) Plan view of small domal microbialites, near contact of Esperanza and Lady Loretta Formations, Phosphate Plant. (g) Vertical section of poorly preserved microbial texture in chert, vicinity of Lady Loretta mine, sample LLD238.

Coin is 3 cm d and bar scale is 1 cm.

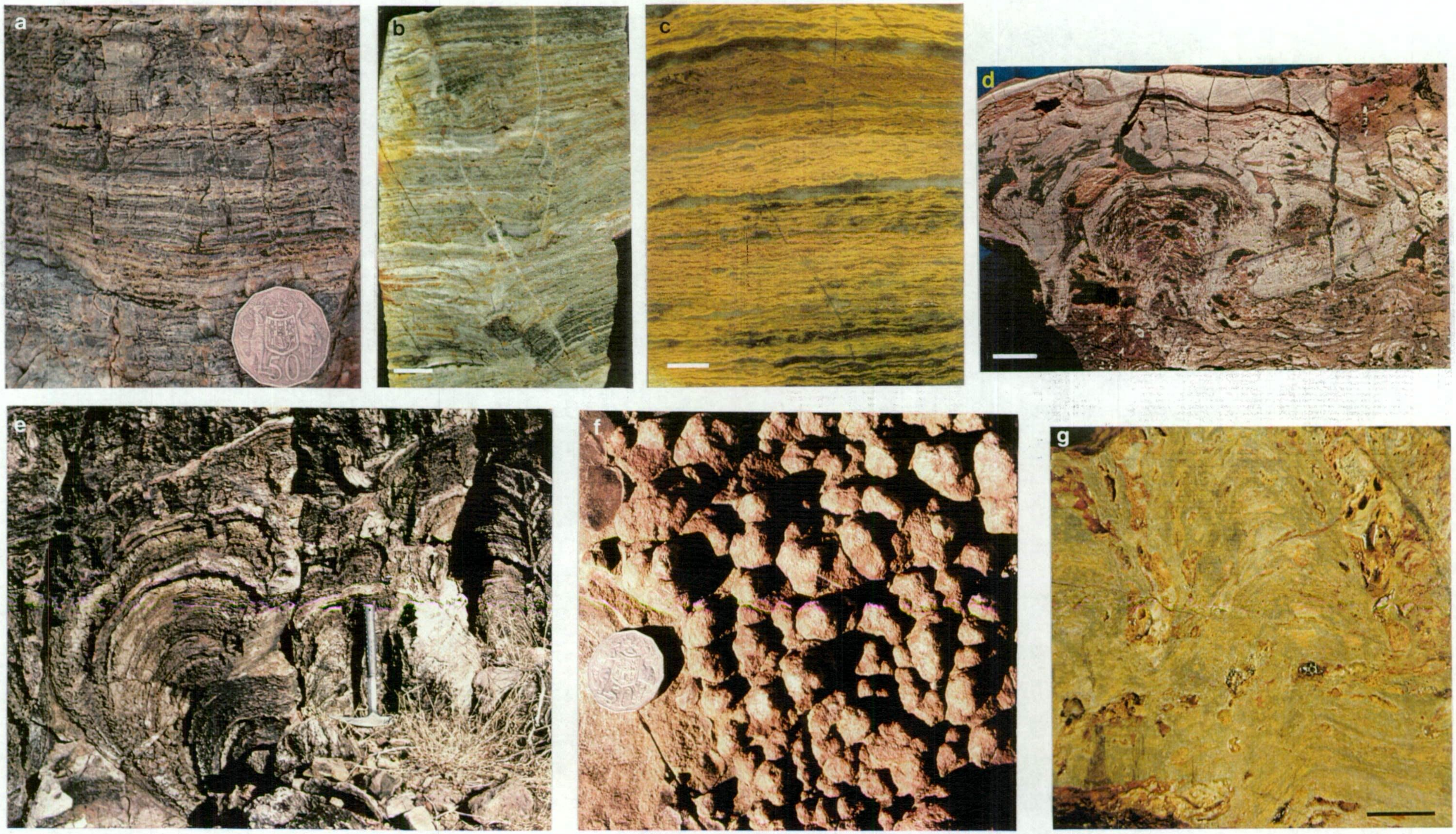
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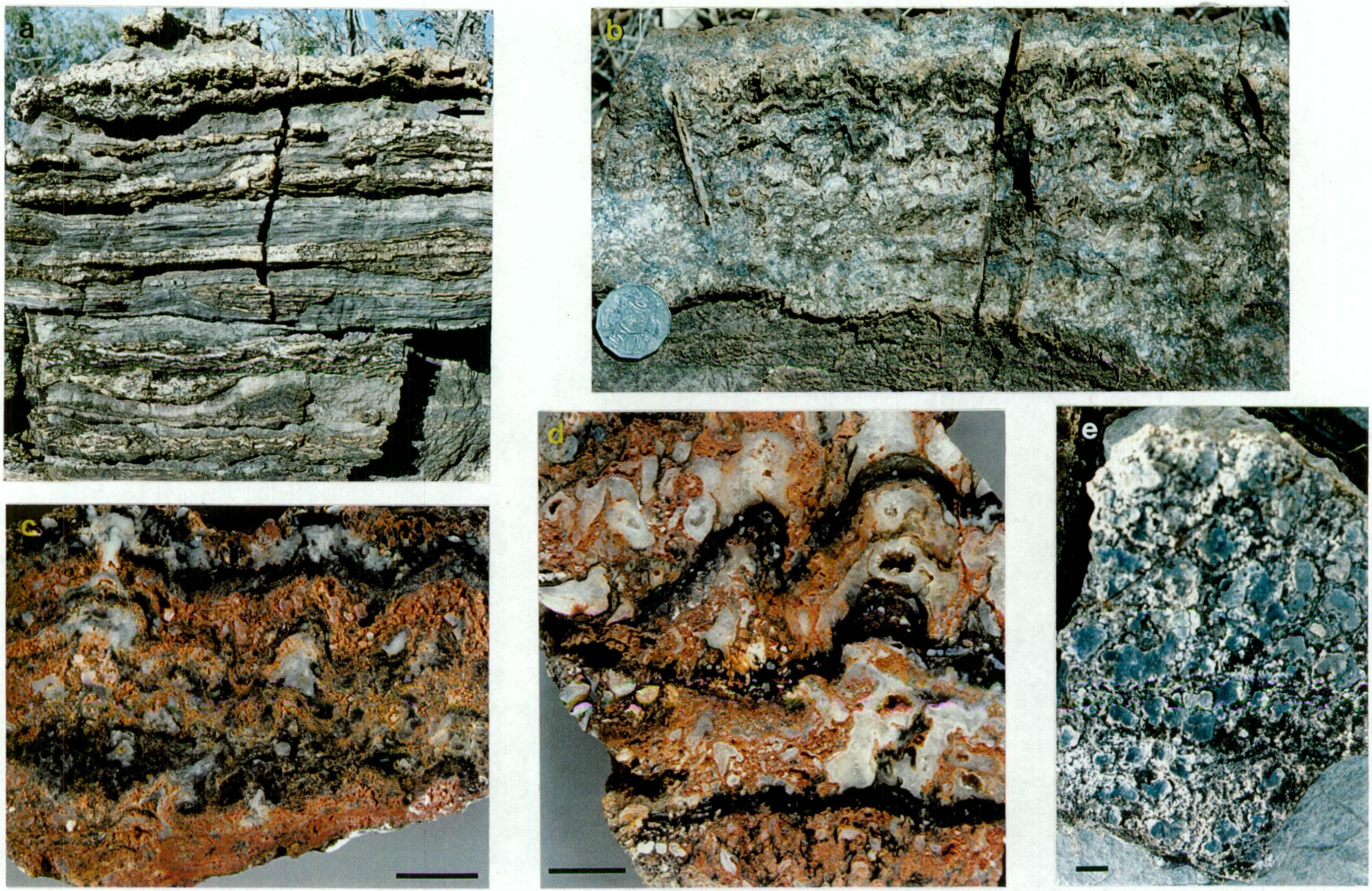
Figure 8-3: Undulatory domal microbialites. (a) Undulose domal microbialite occurs above the coin indicated by the arrow. Section KD1, Kamarga Dome. (b) Detail of specimen shown in (a). (c) Polished slab showing vertical section. Note the relatively thick microbial layers, limonitic material after bedded pyrite and ?fenestral chert, KD3.300. (d) A similar texture from Wangunda where undulatory domal microbialite is associated with desiccation features and an evaporite overprint, WAN325. (e) Plan view of the outcrop shown in (b). Note that the microbial material, now preserved as chert, is broken into curled plates. Coin is 3 cm d and bar scale is 1 cm.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carbonates and shales. The better preserved examples occur on the flanks of Kamarga Dome, where they can be correlated between sections several kilometres apart. This microbialite also occurs over smaller areas at the base of the Lady Loretta Formation in the south including the Phosphate Plant section, east of the mine.

8.6.2 Interpretation

Hoffman (1974) described Proterozoic contorted incipient columnar microbialite alternately interbedded with either limestone rhythmites or siliciclastic mud and interpreted them as basin-floor facies. Despite the superficial similarity, the examples he described lacked the void-fill textures and evaporite and desiccation overprints found in the examples from the Lady Loretta Formation. This microbial texture also resembles the crinkle-mat zone of a Recent evaporitic Persian Gulf lagoon described by Kendall & Skipwith (1986), the modern microbialites from the shallow (<20 m) hypersaline Gotomeer in the Caribbean (Kobluk and Crawford, 1990) and the extant *Lyngbya* mats at Laguna Mormona in Mexico where they grow in conditions varying from a few centimetres of submergence to periodic exposure (Horodyski, 1977). All these modern analogues can be interpreted to suggest very shallow conditions for the examples from the Lady Loretta Formation.

The abundance of primary ?fenestral porosity (now filled by chert), desiccation features and associated evaporites in the examples from the Lady Loretta Formation can be interpreted to suggest shallow water to emergence. These features, and an analogy to extant microbialites and cyanophytes, are consistent with a restricted shallow marine, ?lagoonal/pond environment of deposition.

8.7 COLUMNAR CONICAL MICROBIALITE

8.7.1 Description and Terminology

Both the lower Lady Loretta Formation and the underlying Esperanza Formation contain spectacular examples of silicified columnar conical microbialites commonly referred to in the geological literature as "Conophyton" (Figure 8-4a-d). The form group *Conophyton* contains several genera, is widespread, and occurs throughout the Proterozoic. It is distinguished by the conical form of the laminae which produces a distinct axial zone. Strictly speaking *Conophyton* are not laterally linked and it is debatable whether linked forms should be included within the biological definition of the group (Grey, 1994b). Thus, it is probable that not all examples commonly referred to as "Conophytons" in the Lady Loretta Formation should be assigned to that group and it is unclear if the common name refers to the group or genus. In the absence of adequate biological description, the term "Conophyton" can be misleading.

In the Esperanza Formation, these microbialites form tabular biostromes up to ten metres high and constitute marker horizons that persist along strike for kilometres. Examples from the lower Lady Loretta Formation (briefly described by Hutton and Sweet, 1982) are less well developed, have a greater size range, and commonly occur associated with other high-relief microbialites. Large domal microbialites commonly merge up to columnar conical microbialite to form biostromes or bioherms metres in diameter (see Section 8.11). Sweet and Hutton (1982) and Pringle and David (1983) reported large diameter "Conophyton" from the upper Lady Loretta Formation at Kamarga Dome. The current study confirmed the presence of columnar conical microbialites at these localities and shows that they are discontinuously distributed at similar stratigraphic intervals around the dome. Some examples are nearly upright, but many biostromes have columns consistently inclined at up to 40° from vertical. The material between the columns originally consisted of carbonate cement with little detritus. Many examples are preferentially silicified in the axial zone and between columns (Figure 8-4d). A typical inclined example is shown in Blake (1987, his Figure 43E). A variation on the columnar conical morphology, in which the microbialites are distinctly star-shaped in plan, was recorded from several locations around Kamarga Dome (Figure 8-1fa).

The Lady Loretta Formation also contains a variety of smaller diameter (3-6 cm) unlinked columnar conical microbialites with a typical steeply-conical axial zone. The columns seldom exceed one metre high. Although they do form extensive biostromes in their own right, they only occur associated with other forms of microbialite and are invariably silicified, commonly non-replacively, making identification difficult. Both inclined and elongate forms (Figure 8-1f) are relatively common.

8.7.2 Interpretation

Modern examples of unlinked conical microbialites up to 85 cm high grow in water 1.5 m deep in Lake Clifton in Western Australia (Burne and Moore, 1987). Grey and Moore (1992) described similar examples from Lake Preston.

Previous interpretations of the environment of growth for ancient columnar conical microbialite have varied from lagoonal to shallow marine (Jackson *et al.*, 1987), sheltered tidal flat (Haslett, 1975) to depths of tens or even hundreds of metres (Hoffman, 1976). The evolution and environmental significance of some Proterozoic *Conophytons* are described by Bertrand-Sarfati and Moussine-Pouchkine (1985) who concluded that they grew in low energy marine conditions with an absence of carbonate mud. Donaldson (1976) described laterally linked Proterozoic examples that contained diagenetic barite in axial zone porosity and had little debris between the columns. These were interpreted as subtidal in up to 10 m water depth. Walter *et al.* (1992) suggested that ancient columnar conical forms ranged from deep to shallow subtidal environments, but were the dominant, and often exclusive, microbial component of basinal and slope environments, and occur as a transitional facies in incipient to terminally drowned platform sequences.

The *Conophyton* from the Lady Loretta Formation shown in Blake *et al.* (1987) is superficially similar to specimens from the Mara Dolomite Member of the Emmerugga Dolomite in the McArthur Basin. Jackson *et al.* (1987) and Walter *et al.* (1988) loosely described these as *Conophyton* but they may belong to the form group *Thyssagetacea* (Grey, quoted in Jackson *et al.*, 1987). Previously, all these examples were interpreted as lagoonal.

The star-shaped conical form is similar to *Jacutophyton*-like microbialites from the Amelia Dolomite in the McArthur Basin described by Jackson *et al.* (1987, their Figures 68 and 71). This morphology may have formed as microbial laminae colonised the void between neighbouring columns.

Examples from the Esperanza and lower Lady Loretta Formations in the vicinity of the Lady Loretta mine were assigned to intertidal to supratidal conditions by Harris (1984, 1993) who suggested they were a "Conophyton-type fore-reef". Hutton and Sweet (1982) favoured a subtidal lagoon for the "Conophyton" in the northern outcrops of the lower Lady Loretta Formation.

Overall, the absence of detritus from within the laminae or between the columns may indicate that the primary means of growth was by carbonate precipitation, not trapping and binding of detrital carbonate. It can be assumed that the minimum water depth is the synoptic relief defined by the height of the draped laminae. In this case, some of the larger examples from the Esperanza and Lady Loretta Formation grew in a minimum of 5 to 8 m of water. These large non-elongate, upright, columnar conical forms from the Lady Loretta Formation probably grew in the deepest water conditions colonised by microbialites and a quiet-water sub-fairweather wavebase marine environment is inferred. Smaller, inclined and elongate examples, that grade to other types of microbialite, may have grown in shallower conditions.

8.8 CUSPATE MICROBIALITE

8.8.1 Description

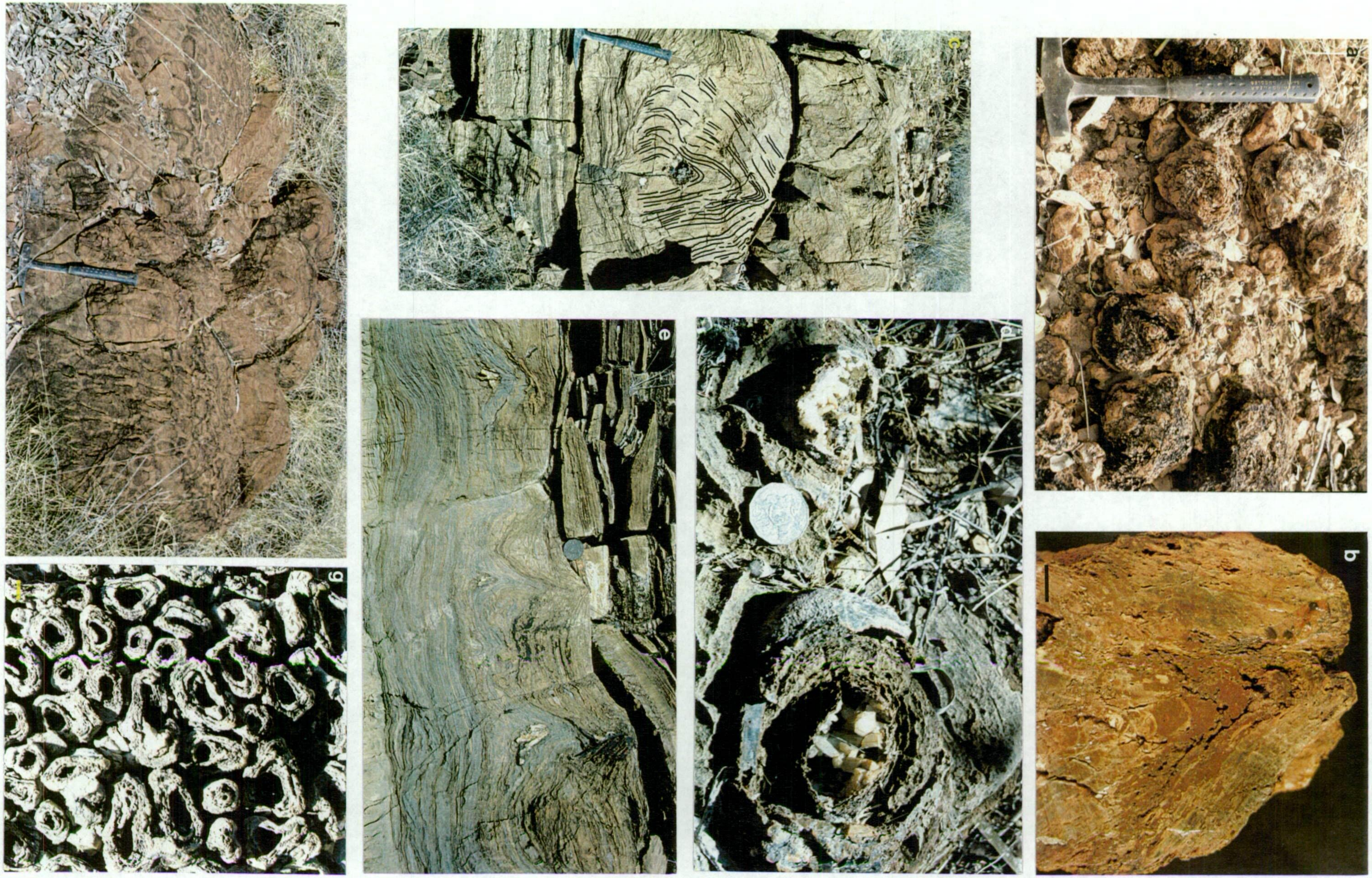
Cuspate microbialites are uncommon in the Lady Loretta Formation and invariably occur in association with, or grade into other forms. Larger examples can form the transition from domes upward to conical columns and may resemble a widely spaced steeply-convex conical form (Figures 8-1e, 8-4e). However, in plan view these cuspate microbialites are commonly elongated into ridges up to ten times longer than their synoptic relief. Similar forms have been reported from the Esperanza Formation on the southern flank of Kamarga Dome (Cooper, 1996). They have also been reported from the mid Proterozoic of Canada (Pelechaty *et al.*, 1991) and the Archaean in Africa (Sumner, 1995). Elongate cuspate microbialites described by Sami and James (1993) are significantly larger (up to 2.0 m wide), and grew taller, than those in the Lady Loretta Formation. Even smaller cuspate examples, about 6 cm from crest to crest, from the upper Lady Loretta Formation, superficially resemble Grey's (1994b) Stromatolite Form 2 from the Glengarry Group of Western Australia.

8.8.2 Interpretation

Sami and James (1993) interpreted elongate cuspate columnar microbialites as having formed in a relatively high energy environment near the platform edge, oriented normal to platform strike. Examples described by Pelečhaty *et al.* (1991) were assigned to a subtidal

Figure 8-4: Columnar, conical, cuspate and pillared microbialites.(a) Pyritised columnar conical microbialite from Mellish Park. This example is associated with a strong evaporitic overprint. (b) Vertical section through one of the cones shown in (a), MEP153. (c) A typical, inclined, columnar conical microbialite with the microbial laminae traced out. The chert nodule in the core contains pyrite. (d) Plan view of columnar conical microbial in outcrop, section KD2, Kamarga Dome. Note chert in core. (e) Near vertical section of cuspate microbialite, Wangunda. The cusps form long ridges in plan view. (f) Pillared columnar microbialite from near the top of the Lady Loretta Formation, section KD3, Kamarga Dome. (g) Rare silicified pillared columnar microbialite shown in plan view, section KD4, Kamarga Dome.

Geology pick for scale, coin is 3 cm d and bar scale is 1 cm.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environment. By analogy, a subtidal environment is also proposed for examples from the Lady Loretta Formation. Since the majority of larger examples are transitional from domes to cones, they may be an intermediate stage developed in response to an overall change in water depth or sediment supply.

8.9 PILLARED COLUMNAR MICROBIALITE

8.9.1 Description

This morphology is characterised by columns, typically about 5-6 cm in diameter, with a moderate to high degree of vertical inheritance (*sensu* Walter, 1976)(Figures 8-1g, 8-4f). They are distinguished from conical columnar forms by their lower lamina profile that ranges from rectangular to variably convex. Consequently, they have no axial zone. Pillared columnar forms also have greater separation between the columns than conical columnar forms of similar diameter. Both varieties of columnar microbialite have, unfortunately, commonly been referred to as "organpipe stromatolites" (*e.g.* Blake, 1987; Harris, 1984; Pringle and David, 1983). Pillared columnar microbialites in the Lady Loretta Formation are rarely elongate or inclined. They are the least affected by silicification and many outcrop examples are still dolomite. Good examples are exposed at Ploughed Mountain and in the KD3 section at Kamarga Dome.

8.9.2 Interpretation

On the basis of sedimentary facies relationships with ooid grainstones and plate breccias and a lateral association with other high-relief microbialites, a shallow subtidal environment of deposition is proposed. The lack of elongation and inclination in comparison to the similar-sized conical forms can be interpreted to suggest that the pillared columnar microbialite grew in quieter water. This is consistent with the interpretation of Young and Long (1976) who described pillared columnar forms from the Proterozoic of northwestern Canada.

Despite the relatively wide spacing between the columns, there appears to have been little primary porosity in this type of microbialite and this may account for the lack of silicification.

8.10 MACRODIGITATE COLUMNAR MICROBIALITE

8.10.1 Description

The Lady Loretta Formation and the underlying Esperanza Formation contain several different types of branching columnar microbialites. One form has individual columns between 0.6 mm to 10 mm in diameter and forms the cap of domal bioherms that are typically a metre or more in diameter (see Section 8.11 and Figure 8-5e-g). This type is widespread, and occurs in both carbonate and sandy facies. It is commonly the only microbialite present in arenaceous lithologies. As such, it is particularly useful in marking the stratigraphic boundary between the Esperanza Formation (with widespread and abundant macrodigitate columnar microbialite of this type) and Lady Loretta Formations (lacking these microbialites) where the transition contains only clastics. Good examples of this are documented by Cooper (1996).

A second type of macrodigitate columnar microbialite, also locally common in both the Esperanza and lower Lady Loretta Formations, (Figure 8-5a) is assigned to the genus *Eucapsiphora* because of the distinctive swelling of the branching columns. These specimens are strongly elongated in plan; the linear column tops resembling ripple marks (Figure 8-1ha). This is a similar habit to that of *Eucapsiphora leakensis* described by Grey (1994a). The illustrated specimen may be *Eucapsiphora paradisa*, originally described from the Esperanza Formation by Cloud and Semikhatov (1969). *Eucapsiphora paradisa* has swollen columns that branch into two or three subparallel to somewhat divergent daughter columns. Columns are commonly connected at their bases or by bridging. Laminae are weakly convex to nearly flat (Grey, 1994a). The columns develop as radiating structures from a large dome (Grey, written correspondence, 1994).

Other unassigned macrodigitate columnar forms are illustrated in Figure 8-5b,c and Figure 8-7 a,b.

The most interesting macrodigitate columnar specimens from the point of the current study are from core of the Lady Loretta Ore Sequence (drillhole 2420ED13, 53.15 m - 52.15 m) (Figure 8-6a-c). Their columns are clearly elongate in plan view but, because the narrow diameter core has been cut at an angle to the columns, it is difficult to assess the variations in column width, inclination, or the nature of branching. Galena occurs as a replacement of microbial laminae and within the barite between the columns. Sphalerite is a non-fabric selective replacement. These macrodigitate columnar microbialites are also present in core from drillholes along sections 2360 (ED12 65.5-70 m), 2390 and 2450 (EI01 43-47 m, ED49 55-57.5 m), indicating that they can be correlated over at least 100 m along the eastern limb of the Small Syncline (see Section 10.5). Figure 8-7d illustrates a possible analogue for the microbialites in the Ore Sequence. This chertified example comes from outcrop near the contact of the Esperanza and Lady Loretta Formations north of the Carlton Fault Zone and is both elongate in plan and inclined relative to bedding.

8.10.2 Interpretation

Digitate columnar microbialites from the Cambrian of South Australia were interpreted to have formed in open to protected intertidal conditions (Haslett, 1975). Columnar forms were most abundant where rates of supply of fine sediment were relatively high. Examples with irregular laminae and poorly developed wall structures were interpreted as having grown on open tidal flats. Several workers have suggested that the specimens from the Lady Loretta Ore Sequence might be indicative of very shallow to ?supratidal conditions (Grey, pers. comm., 1994). Other examples from the Lady Loretta Formation are also assigned to a shallow setting. Sedimentary facies associations are consistent with both open marine and lagoonal environments.

Figure 8-5: Macrodigitate and elongate microbialites. (a) A macrodigitate microbialite with swelling and branching columns and elongation in plan view, sample REC97. This specimen is from near the contact of the Esperanza and Lady Loretta Formations. (b) A tracing from a slab showing much closer-to-parallel columns and branching without pronounced swelling (lower right), MEP149. The columns are circular in plan. (c) Branching macrodigitate form with a wide variation in column widths. (d) Strong elongation in plan view. Compass for scale. (e) to (g) A bioherm of macrodigitate columnar microbialite from the contact of the Esperanza and Lady Loretta Formations. (a) A near vertical axial section through a broken bioherm at Phosphate Plant. (f) Outer skin of the bioherm, note the circular column outline in plan. (g) Author's schematic reconstruction of a cut-away bioherm.
Bar scales in (a) to (c) are 1 cm, bar scale in (g) is 10 cm.

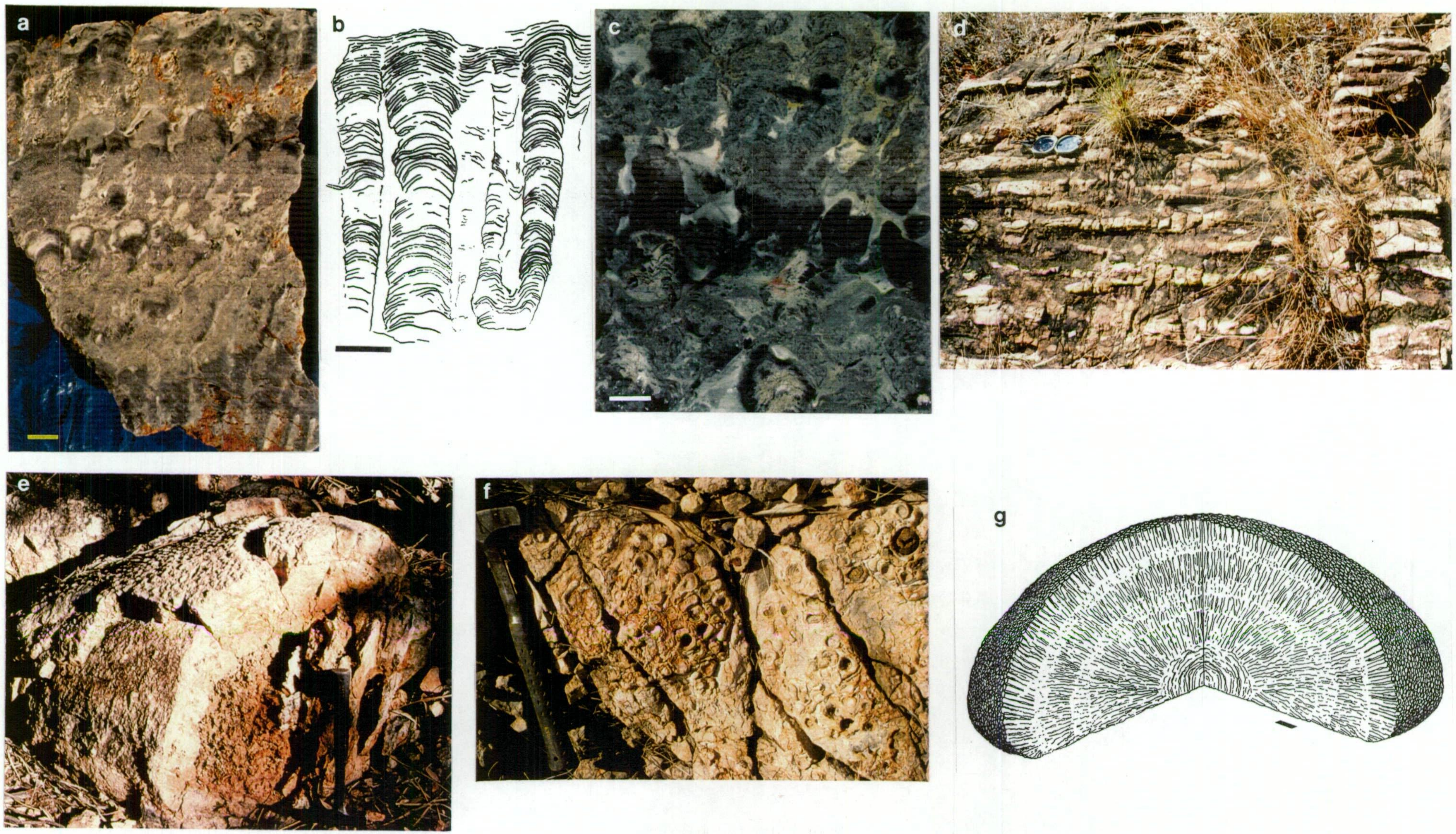

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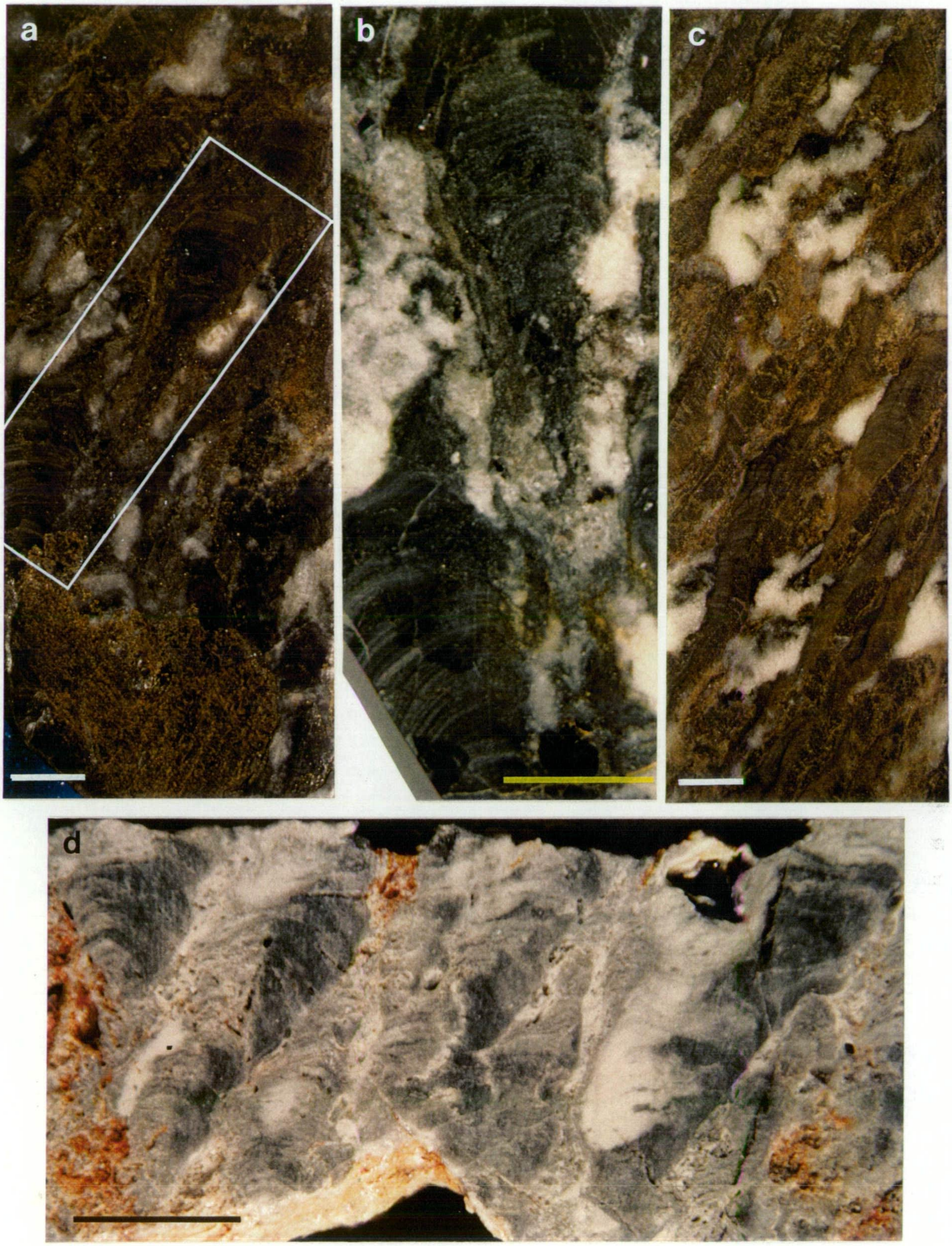
Figure 8-6: Macrodigitate columnar microbialites from the vicinity of the Lady Loretta mine. All these examples are strongly elongate in plan. (a) Example from core of the Ore Sequence. The white material between the columns is barite. The brown material is sphalerite and galena occurs within the microbial laminae. The area marked is shown enlarged in (b), 2420ED13, 52.5 m. (c) A similar texture probably from the same bed, 2420ED13, 53.15 m. (d) Macrodigitate columnar microbialite preserved in chert from outcrop near the contact of Esperanza and Lady Loretta Formations north of the Carlton Fault Zone, LLD237. The columns are both elongated and inclined. The photograph is shown in correct stratigraphic orientation.

Bar scale is 1 cm.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8.11 MINIDIGITATE COLUMNAR MICROBIALITE

8.11.1 Terminology and Description

The present study uses the term "minidigitate" to distinguish these forms from microcrenulated, radially fibrous "microdigitate" tufas described by Hofmann and Jackson (1987) and Grotzinger (1993) that may, or may not, be of biological origin. The minidigitate form also could be termed asperiform (Walter *et al.*, 1992).

This form of microbialite has been described from a single occurrence in the Lady Loretta Formation and was first recognised by McGoldrick (1993) and illustrated in McGoldrick *et al.* (1995). The examples illustrated in Figure 8-7c,d are in core from drillhole 2390EI14 (97.1m) in the Small Syncline at the Lady Loretta mine and consist of branching curved columns about 2 mm wide with convex to rectangular laminae with micro-unconformities. They occur stratigraphically below and may also be laterally equivalent to the macrodigitate forms described above. The intra-ore sedimentary rocks which contain the minidigitate forms also contain locally abundant barite and acicular pseudomorphs after gypsum.

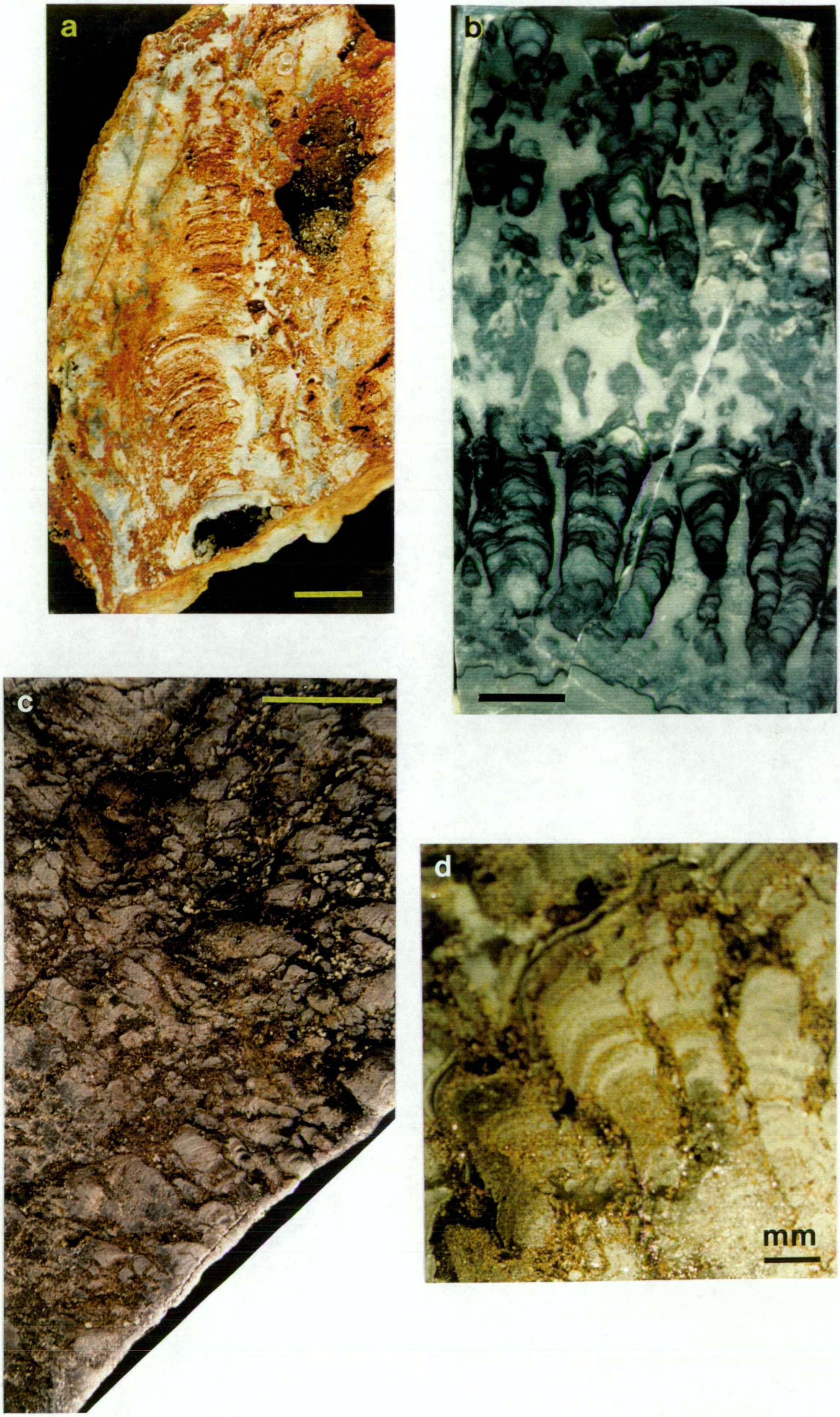
8.11.2 Interpretation and Significance of Minidigitate Microbialites

Possible modern analogues occur on the landward edge of Lake Clifton, WA. They are actually exposed in summer and kept moist only by groundwater seepage (Grey and Thorne, 1985). Ancient examples are invariably assigned to a very shallow peritidal setting. Hoffman (1976) postulated that minidigitate Proterozoic forms grew in supratidal ponds that were perhaps less than a metre deep and Thorne and Seymour (1991) assigned bioherms of minidigitate microbialites to a high intertidal to supratidal facies. By analogy and using the suggested correlation between synoptic relief and palaeo-water depth for this type of microbialite (Grotzinger, 1989), a very shallow setting is envisaged for the specimens from the Lady Loretta Formation.

Contrary to Grotzinger (1989) the present study does not interpret all asperiform microbialites as inorganic precipitates. However, at 1647±4 Ma, these Palaeoproterozoic examples from the Lady Loretta Formation are significant in terms in of the temporal distribution of asperiforms (see Grey and Thorne, 1985, their Fig.12). This has implications for the conclusions drawn by Grotzinger (1989, his Figure 15) regarding the relationship between asperiform microbialites, sulphate evaporites and aragonitic seawater chemistry (see Sections 2.4 and 6.4.5).

Figure 8-7: Macrodigitate and minidigitate microbialites. (a) Macrodigitate columnar microbialite in chert from outcrop north of Carlton Fault Zone, LLD138A. (b) A well-preserved example of macrodigitate columnar microbialite in dolostone from near the contact of the Esperanza and Lady Loretta Formations, core from drillhole CM35, 320.5 m. Note the branching of columns. (c) Minidigitate columnar microbialite in slabbed core of the Ore Sequence, drillhole 2390EI14, 97.1 m. The brown material between the columns is a mixture of carbonate, chert and sphalerite. (d) Close-up of previous, photo of curved face of core.

Bar scales in (a) to (c) are 1 cm, bar scale in (d) is 1 mm.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8.12 BIOHERMS, BIOSTROMES AND REEFS

8.12.1 Description

Several of the microbial morphologies described above grew together to produce structures with considerable synoptic relief. The domal to macrodigitate columnar bioherm depicted in Figure 8-5e-g is typical of the type that occurs at the contact between the Esperanza and Lady Loretta Formations. The other common association is a biostrome of domes merging up through inclined cones to cumulate and, ultimately, prone microbial laminite. Not all these elements are present in every example. Argillaceous clastics were deposited in pockets between the mounds and some of the biggest biostromes have debris aprons similar to examples from the Esperanza Formation.

Interpretation

The spectacular biostromes and bioherms of the Esperanza Formation would have constituted a reef (*sensu* Grotzinger, 1989). Those biostromes from the Esperanza Formation, dominated by upright unlinked columnar conical microbialites, were probably sub-fairweather wavebase. During deposition of the Lady Loretta Formation, domal mounds up to 10 m across and 1.0 m high coexisted with smaller poly-form bioherms and biostromes that had in excess of a metre of synoptic relief. These smaller reefal mounds probably formed on the edge of a lagoon or on a shallow ramp. The larger biostromes with large-diameter inclined columnar conical microbialites were probably in deeper water but still sufficiently shallow to be influenced by wave and current action.

8.13 ELONGATION AND ORIENTATION WITH RESPECT TO CURRENTS AND WAVE ACTION

8.13.1 Description

Non-vertical inclination and elongation in plan are conspicuous features of several different microbial morphologies in the Lady Loretta Formation (Figures 8-1e,f,h; 8-5d; 8-6d). Examples of linked domes, columnar cones, cuspate, macro- and minidigitate forms have all been recorded with elongation aspect ratios of >5:1. Several examples of columnar conical forms grew to became more elongate up-section. Pillared columnar microbialites are only rarely elongate and ratios of individual laminae seldom exceed 3:1. Bioherms and the smaller biostromes commonly display a preferred orientation in plan. Inclination is most common in columnar conical forms but has been recorded from examples of most of the higher-relief forms.

8.13.2 Interpretation

There is no convincing documented relationship between elongation in plan and palaeowater depth, although some workers have suggested a decrease in elongation towards both deeper and shallower ramp settings (see discussion in Grotzinger, 1989). However, elongation may be related to the current direction. Similarly, inclination of microbialites has been related to hydraulic conditions (wave surge and/or tidal strength) and sun angle.

The well-documented examples of living microbialites from Shark Bay, WA show elongation parallel to the direction of sediment transport. In this case it is perpendicular to the shore (Logan *et al.*, 1973). Proterozoic examples of horizontal elongation such as in the Canadian Shaler group (Young and Long, 1976), the Bambui Group of Brazil (Cloud and Dardene, 1973), the Belt Super Group (Horodyski, 1983) or the Rae Group Conophytons (Donaldson, 1976) have been interpreted as evidence of strong currents and at least intermittent turbulence in a shallow subtidal to intertidal setting. Hoffman (1973, 1976) noted that elongation of stromatolites in plan is generally parallel to palaeocurrent direction and commonly parallel to depositional strike and that inclination should be towards the direction of sediment supply. Hoffman (1974) and Sami and James (1993) documented the following:

- elongate domal ridges are probably aligned perpendicular to original platform strike
- low relief microbial pillars are typically inclined, but do not have a preferred orientation
- columnar microbialites are elongate in a platform-normal orientation and inclined up to 45° shoreward
- cuspate columnar forms are inclined up to 40° shoreward.

Conophyton-like columns in the Dungaminnie Formation in the McArthur Basin were interpreted as being inclined toward the sediment supply and into the prevailing currents (Jackson *et al.*, 1987).

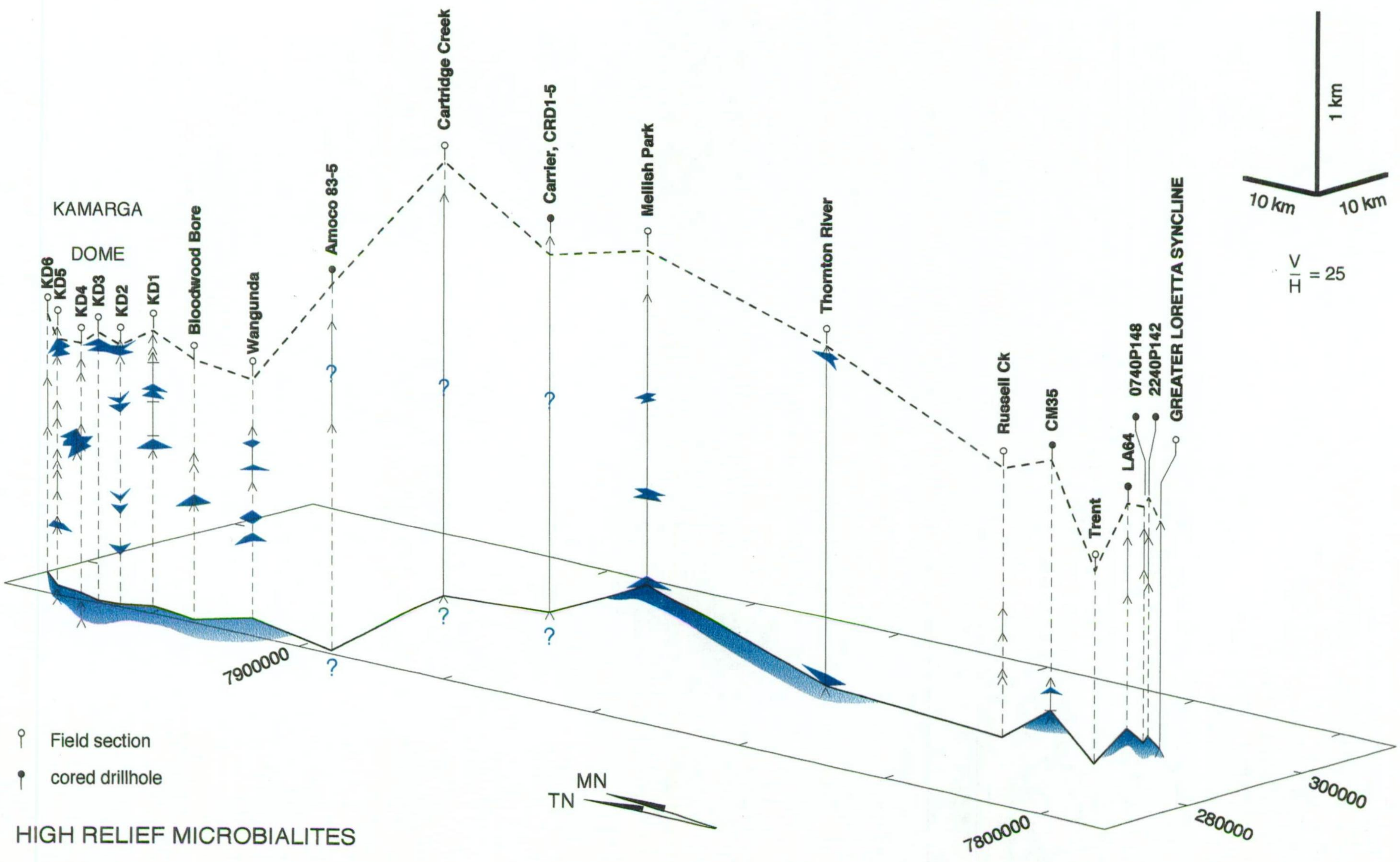
Similar interpretations are plausible for the high-relief microbialites from the Lady Loretta Formation since elongation shows a consistent pattern when compared to the palaeocurrent directions derived from measurements of crossbeds and ripples (see Section 5.5). There are too few data to support the interpretation that inclination could be used to determine the orientation of the palaeo-shoreline.

In the vicinity of the Lady Loretta mine, elongation and inclination of macrodigitate columnar microbialite may be interpreted to indicate more open circulation and stronger water currents, possibly in the intertidal zone. The elongate and inclined minidigitate forms in the Ore Sequence may be a special case since it is possible that they are responding to hydrothermal discharge rather than active circulation in open water.

8.14 SUMMARY

The diversity of microbialite types in the Lady Loretta Formation and their sedimentary facies associations reflect formation in a range of different marine environments. The highest-relief forms appear to be most abundant in the north and are almost exclusively restricted to the lower Lady Loretta Formation in the south (Figure 8-8) and this has implications for the interpretation of ramp/shelf morphology (Section 10.4). The largest non-elongate columnar conical microbialites probably formed sub-fairweather wavebase reefs. Smaller domal and multi-form bioherms developed on the shallow ramp and flanking lagoons. Horizontal elongation (and possibly inclination) are oriented with respect to palaeocurrent directions and probably resulted from wave action and turbulence. Many of the microbialites from within the Ore Sequence and its lateral equivalent are similar to those from elsewhere in the formation. However, the microbialites from the ore itself are conspicuously lower in relief than others from the Ore Sequence Equivalent or from elsewhere in the formation. Rare minidigitate forms from the Ore Sequence may have grown in shallow conditions.

Figure 8-8: Distribution of high-relief microbialites in the Lady Loretta Formation.



HIGH RELIEF MICROBIALITES

Chapter 9 - Evaporites

9. EVAPORITES - ORIGIN AND ENVIRONMENTAL INTERPRETATION

9.1 INTRODUCTION

Like several other formations in the McNamara Group, the Lady Loretta Formation contains widespread and locally abundant evaporite pseudomorphs, casts and moulds (Figure 9-1). The current study interprets the presence of various forms of calcium sulphate evaporite and presents the first evidence of widespread halite in the Lady Loretta Formation including in the vicinity of the Lady Loretta mine. Similar evaporite pseudomorphs have also been described from the host rocks to the Mount Isa ore body (McClay and Carlile, 1978; Neudert, 1983) and in the vicinity of HYC (Walker *et al.*, 1977).

Correct recognition and interpretation of the original evaporitic minerals and textures and their complex diagenesis (see Section 11.4.5) are important adjuncts to sedimentological studies. In comparison with some other workers (*e.g.* McClay and Carlile, 1978), the present study has been deliberately circumspect. In particular, it is important to differentiate between subaqueous evaporites and those that grew as an overprint within the unconsolidated sediment. Equally, it is possible that the incorrect application of a purely uniformitarian approach by some previous workers (see Chapter 2) has resulted in the role of evaporites being over-emphasised as palaeo-environmental indicators and misinterpretation of marine and paralic evaporites as lacustrine.

9.2 GYPSUM PSEUDOMORPHS

9.2.1 Isolated Crystals

Description

Isolated pseudomorphs and moulds of euhedral doubly-terminated acicular and lath-shaped crystals are common throughout a wide range of lithologies in the Lady Loretta Formation. The pseudomorphs are generally several millimetres long and less than a millimetre wide. In clastic facies, they are commonly clustered on, and oriented parallel to, bedding surfaces. The crystals do not exhibit a preferred orientation in dolomitic (Figure 9-2a,b) or microbial facies and, in the latter case, commonly have length to width ratios of >10:1 (Figure 9-2c,d). Pseudomorphs are commonly hollow, sometimes in radiating bundles, with arrow head or swallow tail twinned terminations. It was not possible to accurately measure interfacial angles of such small, poorly preserved pseudomorphs. The majority of original crystals are pseudomorphed by dolomite or length-slow quartz. Rare pseudomorphs consisting of barite and pyrite or intermixed siderite and dolomite occur within the Ore Sequence. Two thin beds of moulds and pseudomorphs, one within the Ore Sequence, can be traced laterally both in outcrop and core for several hundred metres on the eastern limb of the Small Syncline.

Examples of isolated crystals preserved as moulds in chert occur at several stratigraphic levels at Kamarga Dome, Brenda Creek and in outcrop in the vicinity of the Lady Loretta mine.

Figure 9-1: Distribution of evaporite textures in the Lady Loretta Formation.

EVAPORITE OVERPRINT

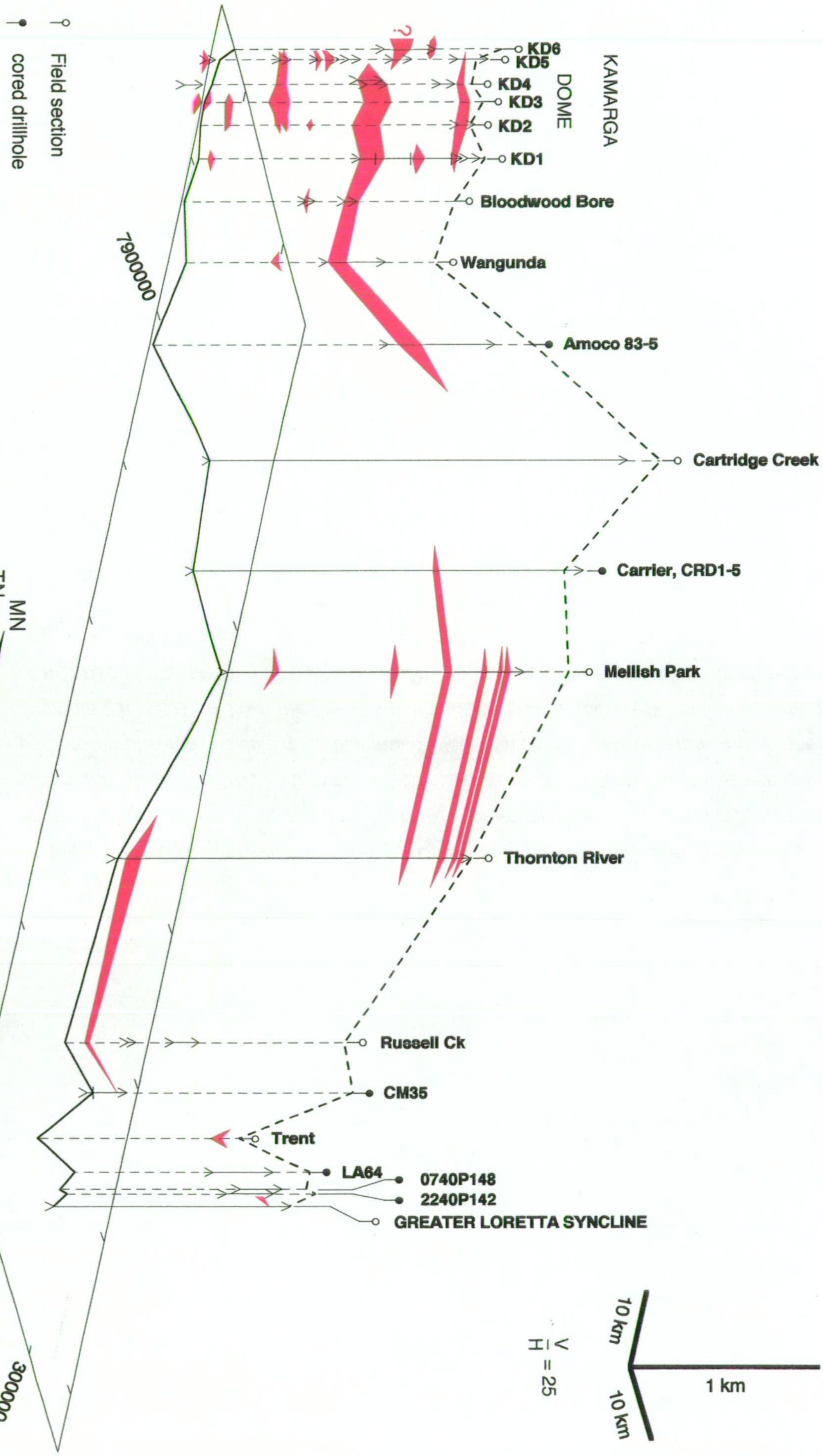
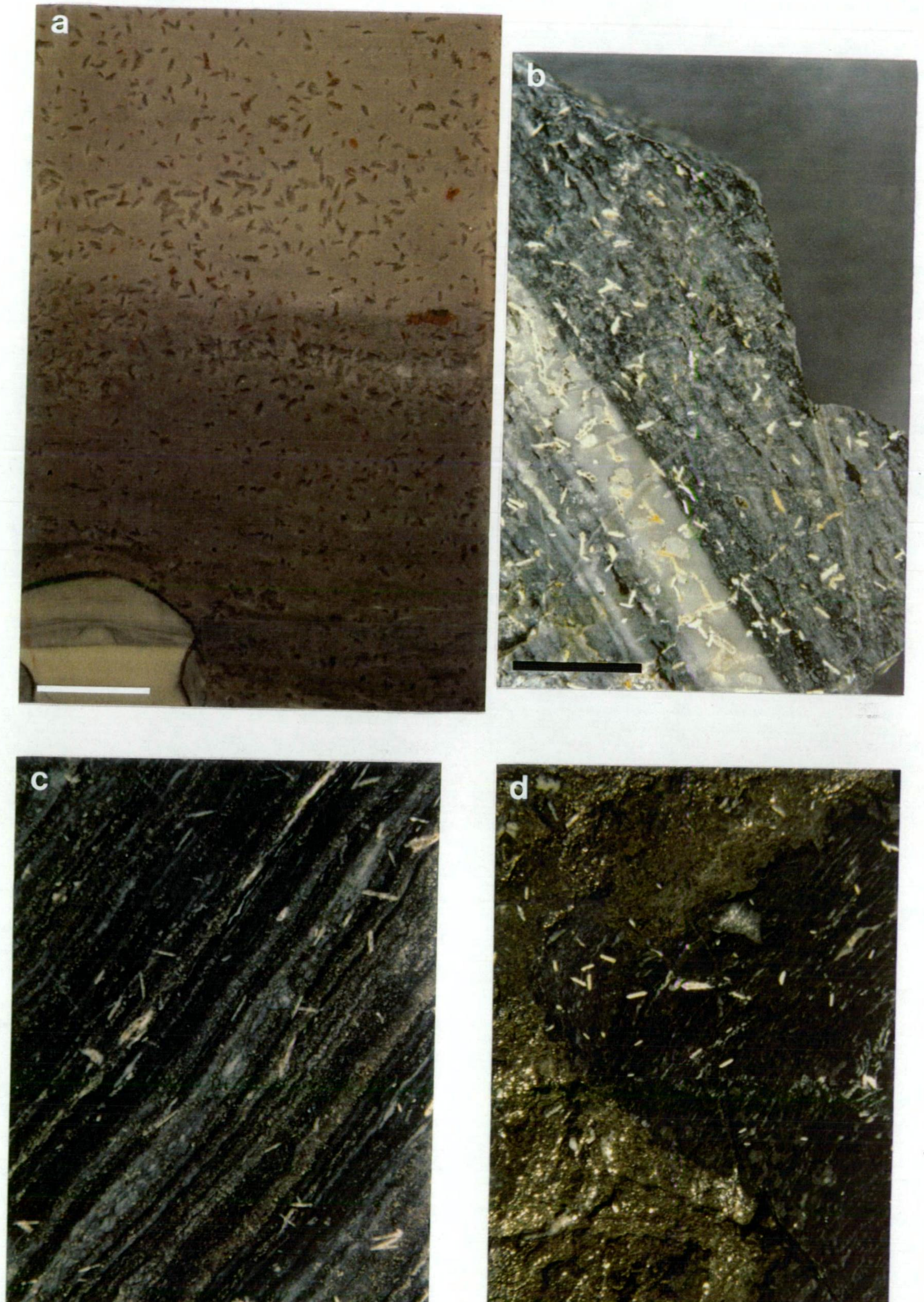


Figure 9-2: Gypsum pseudomorphs. (a) Dolomite pseudomorphs after gypsum in a dolostone bed. Amoco 83-5, 419.2 m. (b) Hollow lath-shaped and acicular pseudomorphs from drillhole 2390ED07, 28.9 m at the Lady Loretta mine. (c) Acicular and lath-shaped pseudomorphs in a possible microbial fabric. Note that some pseudomorphs are twinned. Drillhole 2360ED12, 43.5 in the Ore Sequence, Lady Loretta mine. (d) Doubly-terminated quartz pseudomorphs in a possible original microbial fabric. Note the proximity of reactive pyrite. Drillhole 2420EI28, 66.7 m, near the contact of the Ore Sequence and the Cyclic Unit. All bar scales are 1 cm.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The moulds are almost always parallel to bedding and concentrated along bedding planes. Figure 9-3a,b shows the similarity between examples from the mine and from 75 km away at Brenda Creek.

Other enigmatic crystal pseudomorphs have been recognised at several locations in the Lady Loretta Formation such as those described by Berg (1986) from the Carrier area. Figure 9-3c shows upwardly radiating acicular crystals and vertically aligned crystals within a carbonate mudstone from Brenda Creek. This bed is associated with the other evaporite pseudomorphs discussed here.

Interpretation

Previous workers had identified similar pseudomorphs and moulds from the Lady Loretta Formation. Examples from Brenda Creek (Dorrins *et al.*, 1983), Kamarga Dome (Pringle and David, 1983) and Carrier (Berg, 1986) were interpreted as pseudomorphs of gypsum. Carr (1981) identified swallow tail pseudomorphs of gypsum in the Lower Carbonate Unit at the Lady Loretta mine and McGoldrick (1993) illustrated examples from outcrop of the Ore Sequence Equivalent in the Big Syncline. Walker *et al.* (1977) interpreted similar crystal pseudomorphs from the Palaeoproterozoic McArthur Group as original gypsum or anhydrite.

All previous workers assumed the gypsum crystals to be of evaporitic origin. This is probably true of the majority of examples where this can be corroborated by the presence of more unequivocal sulphate evaporite textures, evidence of halite and/or desiccation features. However, not all isolated gypsum crystals are necessarily of evaporitic origin. Non-evaporitic gypsum, including swallow tail twins, occurs in Pleistocene glacials where it is formed by oxidation of sulphides by high-calcium oxidising ground waters (Bain, 1990). Decomposing pyrite (such as found in the Lady Loretta ore body) produces sulphuric acid that reacts with calcite to produce gypsum. Crystal forms identical to those from modern evaporitic environments can result. This can be seen happening in costean exposures of the Ore Sequence Equivalent in the Big Syncline and other examples from elsewhere are discussed in Sonnenfeld (1984). Gypsum (and anhydrite) are also common hydrothermal minerals. Thus, isolated pseudomorphs of gypsum crystals from the Lady Loretta mine (and other pyritic SSHBM ore bodies) do not necessarily imply evaporitic conditions during deposition of the host sequence.

9.2.2 Discoidal Gypsum

Description

Locally abundant discoidal (hemipyramidal) crystal pseudomorphs, casts and moulds (Figure 9-3d-f) occur in both carbonate and clastic host rocks at numerous localities in the northern Lady Loretta Formation. The crystals are lensoidal in cross section and typically range between 2 mm and 7 mm in the longest dimension. Rare examples exceed 12 mm. The average length to breadth ratio is 3.6:1. Some examples are hollow or internally zoned and intergrown (aggregate) crystals are commonest near the base of beds.

Figure 9-3: (a) Bedding exposure of euhedral gypsum moulds in chert from outcrop in the vicinity of the Lady Loretta mine, LLD212. (b) Bedding exposure of euhedral gypsum moulds in chert from Brenda Creek, BCC180A. (c) Unusual crystal pseudomorphs from Brenda Creek. Note the radiating acicular needles in the centre of photo. Vertical oriented crystals are pseudomorphed in the tear-drop shaped areas and in the lamina on the left, BCC196C. (d) Moulds after discoidal gypsum, bedding plane exposure at Kamarga Dome. (e) Pseudomorphs of discoidal gypsum from a highly ferruginous microbial facies at Mellish Park, MEP154A. (f) Chert pseudomorphs of discoidal gypsum in an ooid grainstone, KD3.288. All bar scales are 1 cm.


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The discoidal crystals are commonly associated with ferruginous facies, preserved as chert or silicified limonitic material, and concentrated in thin beds. Isolated, layered and aggregate (rosette) forms, as defined by Logan (1987), have been recognised. In one spectacular example from Kamarga Dome, discoidal pseudomorphs occur randomly throughout an original ooid grainstone (Figure 9-3f).

Interpretation

This texture is identical to discoidal gypsum crystals for which there are excellent modern analogues. The sabkhat[†] of the Trucial Coast contain displacive lenticular gypsum crystals forming a "gypsum mush" layer in the sabkha profile (Castens-Seidell, 1984; Kendall, 1992). In the Laguna Madre, Texas, intergrown discoidal gypsum crystals increase in size from less than 0.5 mm just below the sediment/water interface to 500 mm at 0.5 m below the surface (Kerr and Thompson, 1963). Crystals 2-6 mm long also grow within the first few centimetres of sediment in the evaporitic environments surrounding Lake MacLeod (Logan, 1987) and other Holocene evaporitic lagoons in WA (Arakel, 1980). Once they are formed, the enclosing surrounding sediment may be removed and the gypsum crystals sorted by elutriation.

There are well-documented Palaeoproterozoic examples of discoidal gypsum pseudomorphs, casts and moulds from the McArthur Basin (Jackson *et al.*, 1978) and from the Urquhart Shale and Native Bee Siltstone at Mount Isa (Neudert, 1983; personal observation).

All the discoidal gypsum pseudomorphs from the Lady Loretta Formation are interpreted to have grown displacively in the very shallow subsurface on the flanks of an evaporitic water body. The presence of abundant gypsum pseudomorphs within an ooid grainstone is good evidence that the evaporites developed as a shallow subsurface overprint while the sediment was brine-saturated.

9.2.3 Bedded and ?Laminated Calcium Sulphate Evaporites

Description

Core from drillhole Amoco 83-5 contains several laminated white to pale brown dolomite and chert beds less than 1 cm thick. In thin section, the chert defines a poorly-preserved fabric of vertically oriented crystals less than a millimetre wide and several millimetres tall within the dolomite laminae. The relict crystals widen upwards. These beds are closely associated with displacive gypsum/anhydrite pseudomorphs and small cauliflower cherts.

At Trent, distinctive chert beds containing two layers (Figure 9-5c) can be traced for > 150 m along strike. The basal portion of each bed varies from finely laminated to nodular. This is overlain by a thicker unit (up to 25 cm) with an internal texture similar to that of cauliflower cherts. This unit occurs within a sequence of slightly dolomitic oxidised siltstones containing sporadic discoidal gypsum pseudomorphs.

Similar chert beds up to 20 cm thick occur at Mellish Park. They are continuously

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[†] *Sabkhat is the preferred plural of sabkha.*

exposed for > 200 m along strike and can be traced to another outcrop at the same stratigraphic level about 300 m away which also contains discoidal gypsum pseudomorphs, low-relief microbialites with a strong evaporitic overprint and locally abundant bedded limonite after pyrite. Internally, the chert beds vary from laminated to wavy and anastomosing. No relict crystals are visible.

Pringle and David (1983) noted a similar association of unusual laminated to thin bedded chert and displacive evaporite pseudomorphs in the Lady Loretta Formation at Kamarga Dome. These beds were relocated during the present study and were traced laterally to a small bedding-parallel fault.

Gypsum beds (<5 cm thick) were described by Carr (1974, 1983) from core of the Lower Carbonate Unit at the Lady Loretta mine. Although this stratigraphic interval is characterised by gypsum veinlets, Carr (1974) recognised these beds as texturally distinct.

Interpretation

Carr (1974) suggested that the bedded gypsum at the Lady Loretta mine was "sedimentary" and implied an evaporitic origin. This material could not be investigated further as the core is no longer available and other intersections of the same stratigraphic interval have deteriorated badly.

The upper portion of the beds at Trent may be a laterally extensive bed of former sulphate evaporite although it is not possible to ascertain if this was a subaqueous deposit or a displacive growth. The lower nodular and laminated textures are also interpreted as former sulphate evaporite.

Pringle and David (1983) interpreted the laminated chert and dolomite from Kamarga Dome as relict laminated evaporite. Most workers have considered that the presence of primary millimetre-spaced laminae in ancient calcium sulphate beds can be used as an indicator of subaqueous deposition (*e.g.* Warren and Kendall, 1985). As such, this would be rare for the Lady Loretta Formation where the majority of evaporite pseudomorphs identified to date are an intra-sediment overprint. Laminated evaporites can form in very different settings, ranging from deep basinal to extremely shallow (see discussion in Peryt, 1994). The deep water forms are generally thicker and more laterally continuous than examples from the Lady Loretta Formation. Sedimentary facies relationships discussed in Chapter 10 can be interpreted to indicate that a shallow setting is more appropriate. In this case, possible analogues of the laminated facies have been described as laminar gypsite and occur in the shallow evaporitic pond stage of Holocene evaporitic lagoons (Arakel, 1980). Other examples occur in the Recent very shallow water (<50 cm) hypersaline pool in Ras Mohamad (Kushnir, 1981). Laminar gypsite is obviously a very shallow subaqueous deposit. However, similar laminated textures (the "compactite" of Langbein, 1987) can also be produced during the diagenesis of other evaporite facies.

The association of unusual laminated to thin bedded chert and displacive evaporite pseudomorphs with a bedding-parallel fault at Kamarga Dome might be expected in an originally evaporitic facies that would constitute a plane of weakness and possibly liberate fluids during diagenesis. However, an origin associated with fluid movement along the fault itself cannot be discounted and the pseudomorphs might not be primary precipitates.

Thus, despite the appropriate sedimentary facies associations and the similarity to Recent laminar gypsite, the preserved textures from the Lady Loretta Formation are not sufficient to unequivocally infer subaqueous deposition in a shallow hypersaline pool.

Wavy and anastomosing sulphate evaporite beds, such as those preserved as pseudomorphs at Mellish Park and Trent, are produced in agitated or current swept environments but are not diagnostic of any particular depth (Schreiber *et al.*, 1973).

Collectively, these examples can be interpreted to suggest the presence of bedded sulphate evaporite at least locally in the Lady Loretta Formation, but it is important to note that they are not unequivocal evidence and they are not volumetrically significant.

9.3 ANHYDRITE PSEUDOMORPHS

9.3.1 The Gypsum-Anhydrite Transformation

Upon burial, gypsum is transformed to anhydrite. This process involves a 40% decrease in volume, producing morphological changes that result in characteristic textures. If the process is reversed, as commonly occurs, by rehydration during emergence or groundwater movement, further morphological changes will occur. These transformations, as described by Langbein (1987), Sonnenfeld (1984) and Warren and Kendall (1985), can complicate the interpretation of ancient sulphate evaporite textures.

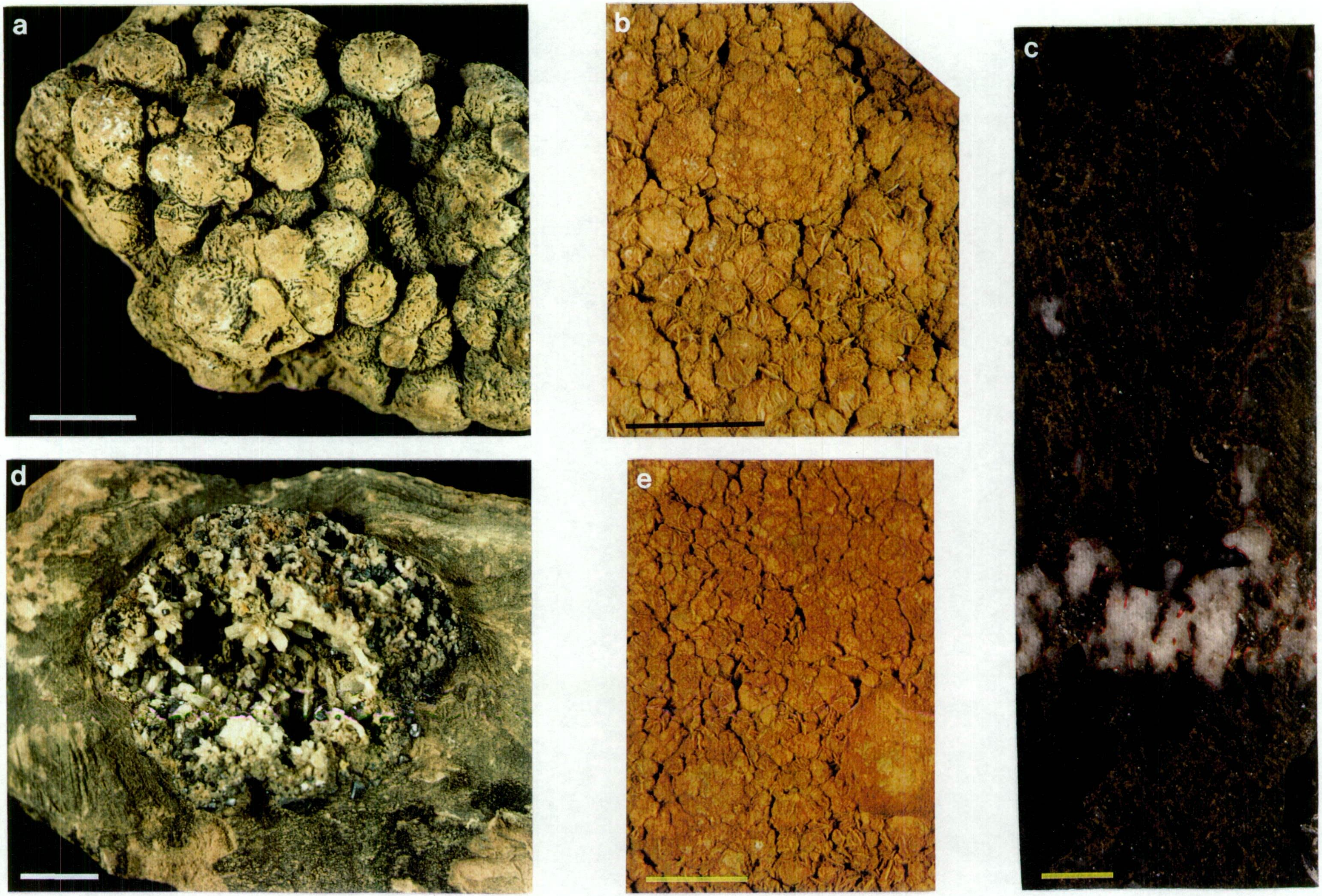
9.3.2 Nodular Anhydrite and Cauliflower Cherts

Description

Cauliflower-like chert nodules are widespread and locally abundant in the northern exposures of the Lady Loretta Formation and were first documented by Sweet and Hutton (1980) and Hutton and Wilson (1984, 1985). They are present in the Thornton River type section but are not mentioned in Hutton and Wilson's (1984) description. The chert nodules occur in bedded and microbially laminated carbonates and mixed carbonate/siliciclastic lithologies. Isolated nodules are present in float from the Trent area and are commonest in red-bed siltstones at a similar lithostratigraphic level to the Ore Sequence.

Typical chert nodules from the Lady Loretta Formation (Figure 9-5a) range up to 15 cm diameter and 6 cm thick and are elongate parallel to bedding. Exceptional examples exceed 30 cm diameter. In several localities at Kamarga Dome and at Trent, the nodules coalesce to form beds. The laminae of the host sediment commonly curve around the nodules. The upper surfaces of the nodules are botryoidal and, in many examples, can be seen to be composed of a mesh of chert lathes (Figure 9-4a,b). In other

Figure 9-4: (a) Cauliflower chert with bladed crystal pseudomorphs, KD3.295. (b) Close-up of the bladed crystals on the surface of a large cauliflower chert produced by coalescing nodules, WAN321. (c) Contorted barite bed resembling enterolithic anhydrite (outlined in red) cross-cutting a digitate microbial texture (outlined in blue). The brown material constituting most of the remainder of the specimen is sphalerite, 2420ED13, 55 m. Note that the barite bed is much more contorted than the microbialites and physically displaces them. (d) A broken cauliflower chert still embedded in its dolostone host. Euhedral quartz crystals, traces of pyrite (now mostly haematite), galena and chalcopyrite are visible, KD1.331. (e) A texture very similar to (b) from the top of a chert bed in the vicinity of the Lady Loretta mine, LLD28B. Bar scale is 1 cm.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e

examples (*e.g.* sample KD5.360) the internal fabric consists of smaller discrete chert nodules towards the outside that coalesce to a solid mass in the centre. In thin section, the smaller nodules contain a concentric zonation or have a relict decussate (random pile-of-bricks) texture. The cauliflower-like cherts from Kamarga Dome outcrops of the Lady Loretta Formation are noteworthy in that they contain visible trace base metal mineralisation (Figure 9-4d). This was also noted by Sweet and Hutton (1980) and Pringle and David (1983). These cauliflower cherts contain inclusions of barite; rare anhydrite, chalcopyrite, pyrite and galena. Isolated anhydrite inclusions are in optical continuity. The internal morphology is described in more detail in Section 11.4.2.

Core from drillhole Amoco 83-5 contains similar concentrically zoned nodules, up to 2.5 cm across. These consist dominantly of chert, but also contain dolomite, siderite and pyrite.

Interpretation

All these examples have been interpreted previously as cauliflower cherts. Similar cauliflower cherts have been demonstrated to be pseudomorphs of anhydrite nodules (Chowns and Elkins, 1974) such as grow displacively within supratidal sediments in modern marine sabkhat. The nodules form by a combination of primary anhydrite precipitation and conversion of primary gypsum to anhydrite. However, the presence of nodular evaporite alone does not characterise a sabkha sequence (Warren and Kendall, 1985).

Cauliflower cherts are relatively common throughout the Proterozoic and Cambrian of Australia. Examples have been documented by Dunster (1987), Hesse (1989), Jackson *et al.* (1987), Milliken (1979), Radke (1982) and Walker *et al.* (1977), amongst others. In all cases, an evaporitic origin was inferred. Alternative mechanisms that produce superficially similar gypsum nodules include:

- precipitation by methanogenic bacteria, as occurs 1-3 m subsurface at the entrance to the Baltic Sea (Sonnenfeld, 1984)
- displacive growth during deep burial diagenesis (Machel and Burton, 1991; Machel, 1993)
- displacive growth in the shallow subsurface of sediments deposited in more than 2000 m of water (Ross and Degens, 1969).

It is important to stress that the internal textures, sulphate inclusions and complex diagenesis (see Section 11.4.2) of the cauliflower cherts from the Lady Loretta Formation are most indicative of an evaporite precursor. These cauliflower cherts may be quite different from some chert nodules described from other base metal host packages (*e.g.* the Urquhart Shale or Barney Creek Formation).

The significance of the base metals in the cauliflower cherts for establishing a relative timing of mineralisation at Kamarga Dome is discussed in Section 11.4.2.

9.3.3 Bedded Anhydrite - Coalescing Nodules and Enterolithic Structures

Coalescing Nodules - Description

Unusual beds consisting of tightly-packed coalescing chert nodules, similar to cauliflower cherts, have been recorded from several localities in the Lady Loretta Formation. Such fabrics are preserved in outcrop at Brenda Creek, Trent, Bloodwood Bore and in several sections on the western flanks of Kamarga Dome. Another thin (<5 cm) chert bed in outcrop north of the Carlton Fault Zone in the vicinity of the Lady Loretta mine has an upper surface very similar to textures observed in cauliflower cherts (Figure 9-4e). Cores from the less-deformed barite at the Lady Loretta mine contain unusual nodular textures previously illustrated by Aheimer (1994) and McGoldrick *et al.* (1995). Figure 9-5a shows radially arranged crystals in barite spherules. The nodules shown in Figure 9-5b contain visible galena. The original host rock, which forms a network between the nodules, has been largely replaced by sphalerite. This network is a truly nodular texture and not the result of tectonic rodding of barite as seen elsewhere in core.

Enterolithic Structures - Description

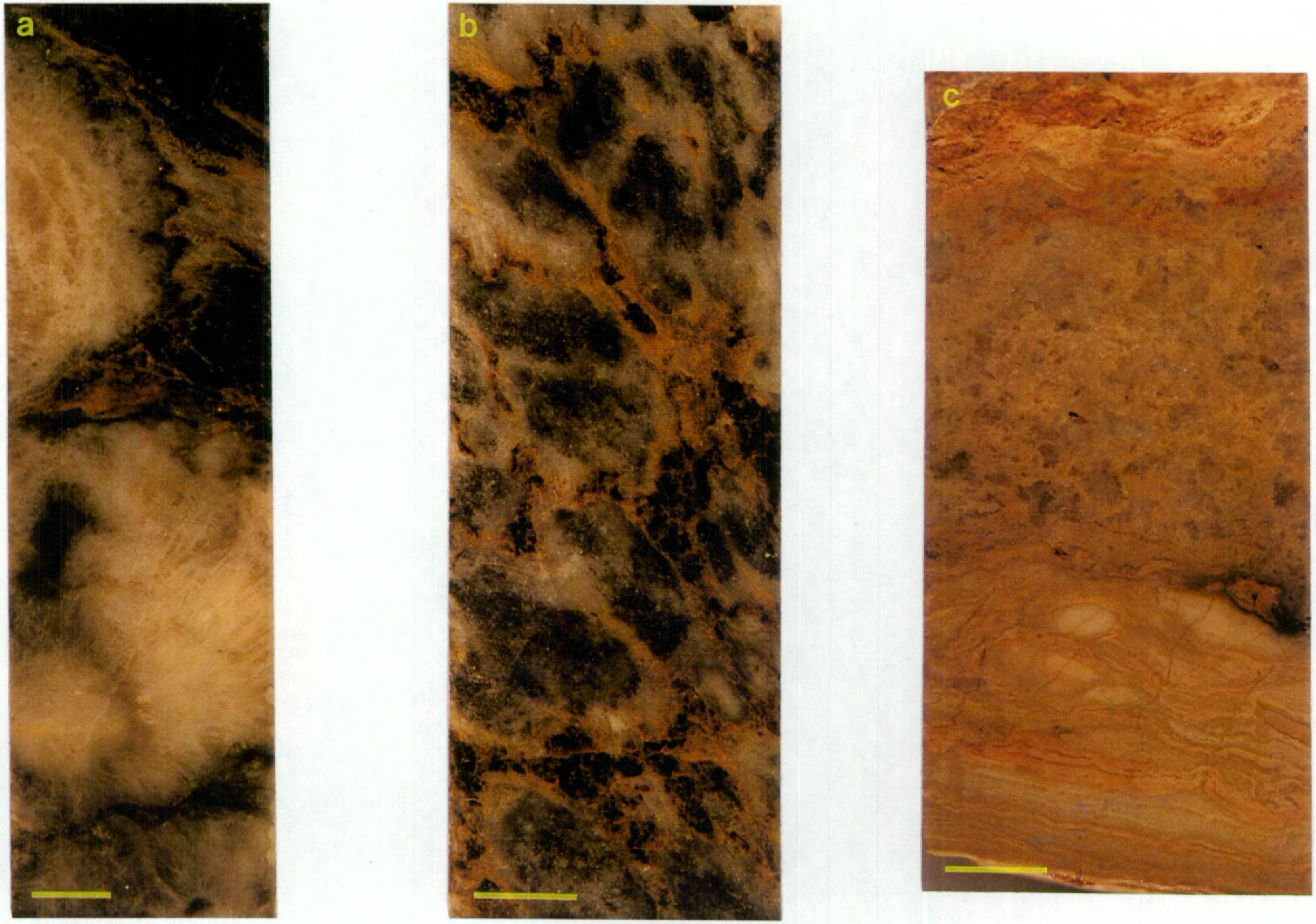
Ptygmatic-like folded chert beds occur in outcrop at Bloodwood Bore, Trent and the western flanks of Kamarga Dome. They are invariably associated with the coalescing nodules described above. A similar texture occurs on a smaller scale in a barite bed that cross-cuts a microbial fabric in the Ore Sequence at Lady Loretta mine (Figure 9-4 c).

Interpretation

Where previously recognised in the Lady Loretta Formation away from the mine, these textures have been interpreted as chicken-wire or enterolithic anhydrite respectively (Pringle and David, 1983; Dorrins *et al.*, 1983; Sweet *et al.*, 1993). These examples are similar to numerous other ancient examples (*e.g.* Dean and Schreiber, 1978; Jackson *et al.*, 1987; Peryt, 1994) that also have been interpreted as pseudomorphs of anhydrite, as forms in the sediment profile of modern sabkhat. Studies of modern analogues show that chicken-wire texture is generated in the subsurface as growing sulphate evaporite nodules coalesce in layers parallel to bedding. The microscopic orientation of the crystal lathes changes from originally subparallel to bedding, to parallel to the edges of the coalescing nodules (Shearman, 1978). Most sediment is displaced vertically as the nodules grow. The remaining sediment forms stringers between the nodules giving rise to the chicken-wire texture. Most workers consider that a combination of continued growth and the volume change associated with the conversion of anhydrite to gypsum result in contortion into the enterolithic structure as seen in modern sabkhat. An alternative mechanism involving subaqueous deposition was proposed by Castens-Seidell and Hardie (1983) and discussed in Demicco and Hardie (1994).

When considered in relation to the other evaporite pseudomorphs and to the sedimentary structures in the host rocks, these examples of coalescing nodules and enterolithic beds from the Lady Loretta Formation can be interpreted as displacive growth

Figure 9-5: (a and b) Possible evaporitic textures from core at the Lady Loretta mine. (a) Radially arranged acicular barite crystals in a spherulitic texture, 2360EI10, 65.2 m. This texture is along strike from the pseudomorphs illustrated in Figure 9-2c. (b) A nodular barite texture overlying the sample shown in Figure 9-5a, 2360EI10, 59.5 m. (c) Laminated and nodular texture overlain by a chert bed with an internal texture similar to cauliflower cherts, Outcrop at Trent, to the west of the Lady Loretta mine. TRE115. Bar scales are 1 cm.


a
b
c

in an environment similar to a modern Trucial Coast sabkha.

Examples from the Ore Sequence at the Lady Loretta mine are more problematic given the intense structural deformation and the uncertainty of the origin of the barite but the possibility that the barite is a displacive sulphate evaporite should not be discounted.

9.4 HALITE PSEUDOMORPHS

9.4.1 Pagoda and Reticulate Halite

Description

The Lady Loretta Formation contains several good examples of extraordinary, delicate branching dendritic chert pseudomorphs (Figure 9-6a,b). They are confined to 2-3 cm thick beds in silicified dolostone and dolomitic siltstones from several locations at Brenda Creek, Wangunda and Kamarga Dome. In one case, the pseudomorphs are arranged into an orthogonal network associated with casts of small hoppers and a possible solution collapse breccia. In another example, pagoda-like crystals appear to have grown displacively and are the corners of an incomplete cube.

Interpretation

Southgate (pers. comm., 1995) identified these pseudomorphs as relict reticulate and pagoda halite crystals similar to those for which he produced experimental analogues (Southgate, 1982). Dendritic halite crystal forms have been observed growing on the floors of shallow brine pools in artificial salinas (Melvin, 1991). Dunster (1987) documented Cambrian pagoda-forms that are still halite. Palaeoproterozoic pseudomorphs were described from the Kennedy Siltstone near Mount Isa (Neudert, 1983).

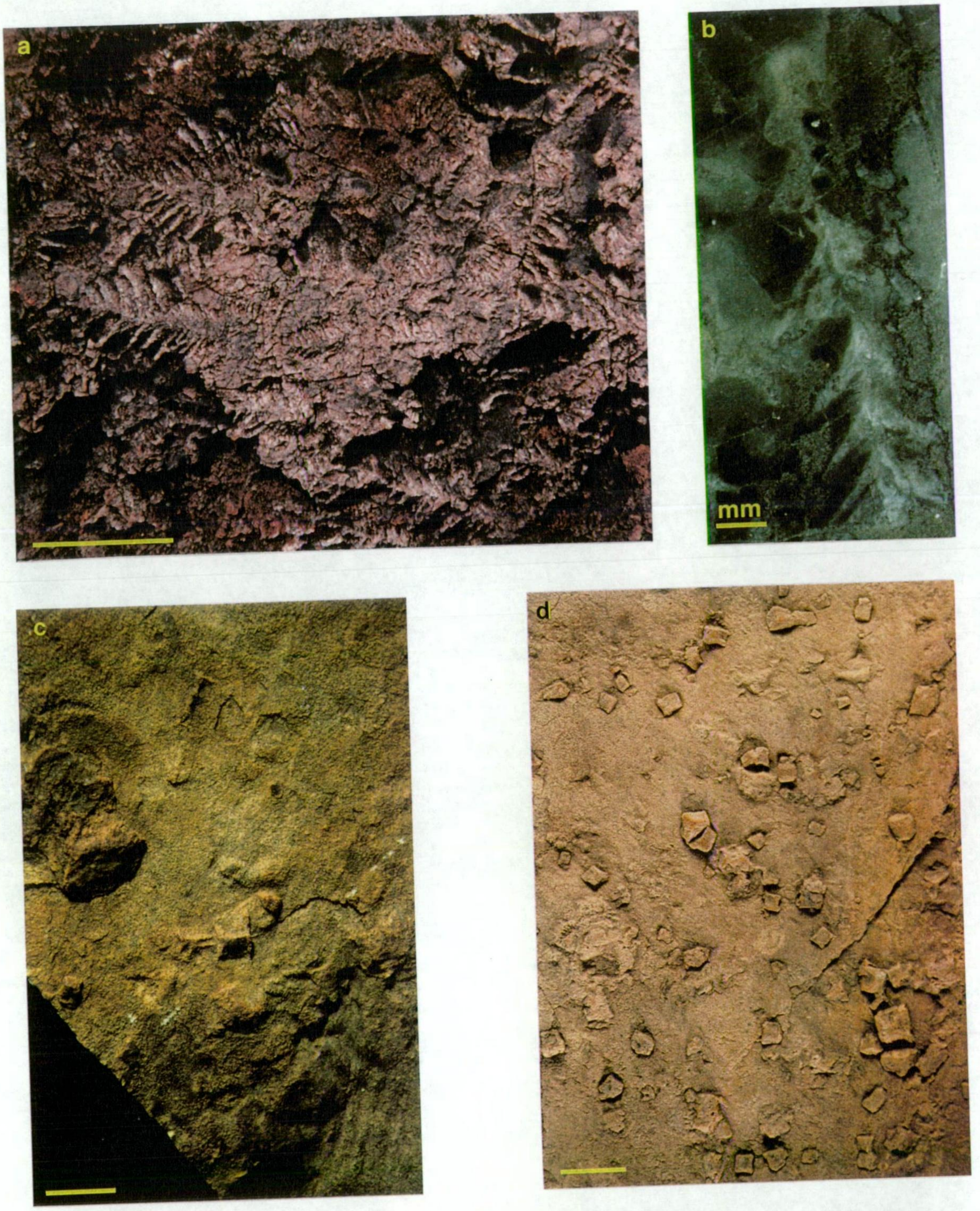
There may be several methods of formation of the original halite crystals. Southgate (1982) favoured nucleation on the bottom of a shallow brine pool, with dendritic halite crystals forming:

- if evaporation proceeds to the point where only the supersaturated layer remains as a thin sheet
- if the supersaturated layer sinks to the bottom during an overturn of a stratified body of water
- in the presence of certain organic or inorganic substances such as humic acid or potassium ferricyanide (Southgate, 1982; Melvin, 1991).

However, Neudert (1983) and Warren (1991, 1996) showed pagoda halite as a displacive secondary evaporite forming in the capillary zone of shallow saline mudflat or sabkha sediments where pore brines are at halite saturation.

In the present study, the reticulate forms that constitute a network are interpreted as a bottom precipitate in a very thin surface film of brine and the isolated pagoda forms are interpreted as an intra-sediment growth. This is consistent with both Southgate's (1982) experimental work and evidence of displacive growth respectively.

Figure 9-6: Halite textures. (a) Reticulate and pagoda halite pseudomorphs in chert, BCC189. (b) Close-up of a pagoda halite from previous location. (c) Halite casts from sandstone in Big Syncline, sample LLD6. (d) Halite casts from the Bloodwood Bore section. Stepped faces are visible on some of the larger examples.(e) A mould of a halite hopper, Kamarga Dome, KD3.290C. (f) Halite casts from section KD2, Kamarga Dome. (g) Halite casts preserved in chert from the Greater Loretta Syncline. Bar scale for (b) is 1 mm, remainder are 1 cm.


a
b
mm
c
d
e
f
g

9.4.2 Cubic Hoppers

Description

Cubic casts and moulds up to 5 cm across, some of which have distinctive stepped faces, are locally common in fine-grained arenaceous and mixed carbonate/siliciclastic lithologies throughout much of the outcrop of the Lady Loretta Formation. Casts are more common than moulds and good examples are exposed at Bloodwood Bore, Brenda Creek, Kamarga Dome and Wangunda (Figure 9-6c-d). Both casts and moulds are dispersed within thin beds or are concentrated on bedding surfaces. Clusters of casts were observed in swales between ripples but were absent from scours and washout rills on the same ripple pavement. At their most abundant, the casts anastomose into a silicified chaotic boxwork. Rare moulds occur in fine grained sandstone at Trent. During the present study, rare casts identical to those from elsewhere in the formation were collected from surface outcrop of the dolomitic sandstone in the core of the Big Syncline at the Lady Loretta ore body (Figure 9-6c). Similar features were observed in a chert bed in the Greater Loretta Syncline (Figure 9-6f). An empirical observation of the examples in the Lady Loretta Formation was that casts oriented with edges or corners up were more likely to have stepped faces than those oriented face up.

Interpretation

Prior to the current study, cubic casts from the Lady Loretta Formation at Brenda Creek (McGoldrick, 1993) and Wangunda (Dorrins *et al.*, 1983) had been identified as pseudomorphs of halite. Much more widespread and convincing examples were documented during this study. Other Palaeoproterozoic examples are locally abundant in the McArthur Basin (notably the Mallapunya Formation). These examples are described in Jackson *et al.* (1987). Neudert (1983) illustrated other Palaeoproterozoic cubic halite casts and moulds from the Kennedy Siltstone.

All these ancient examples are directly analogous to modern cubic halite that forms in peripheral sediments around salinas. Halite crystals that grow displacively in brine-saturated sediment may retain a solid euhedral cubic shape by simply physically displacing the surrounding matrix. Alternately, zoned inclusions of the enclosing sediment may be incorporated within the halite crystal. Since growth is more intensive at the edges and corners, skeletal crystals with hopper-like pyramidal hollows will form on each cube face resulting in cubic skeletal hoppers (Raup, 1970). This may explain why most skeletal hoppers are not face up. The formation of displacive halite hoppers requires a supersaturated host matrix and so many workers have postulated that such halite can only form in the subsurface below sabkhat or mudflats adjacent to salinas or playas. The zoning may reflect fluctuating levels of brine saturation as would be expected in the brine-logged sediment around small, shallow brine pools. Alternately, it might reflect seasonal or even diurnal variations in the brine composition of a much larger brine pool (possibly with a marine connection). The absence of halite hoppers from ripple crests and from washout rills can be interpreted to suggest that the examples from the Lady Loretta Formation formed very soon after deposition of the sediment.

9.5 DISCUSSION

Evaporites can accumulate in four ways:

- intrasediment precipitates
- subaqueous bottom precipitates
- subaqueous cumulates
- clastic particles.

Of these, only the first is volumetrically important in the Lady Loretta Formation. This is consistent with derivation from marine waters in paralic environments where the sediments would have been brine-logged. The presence of evaporite pseudomorphs in the original porosity of subtidal facies (such as ooid grainstone and high-relief microbialites) is good evidence that the majority of evaporites formed as a subsurface overprint. It is important to note that there are no modern analogues for these ancient platform evaporites (see Section 2.4). No unequivocal examples of subaqueous precipitates or cumulates, as would be expected from a lacustrine setting, have been identified to date. Alkaline evaporite pseudomorphs, as form in a modern lacustrine setting, are also conspicuously absent. Thus, the evidence of evaporites in the Lady Loretta Formation supports a shallow marine setting. This contrasts sharply with interpretations of parts of the contemporaneous Mount Isa Group (Neudert, 1983) and some formations in the McArthur Basin (Jackson *et al.*, 1987) where, despite describing identical evaporitic textures, a lacustrine setting has been inferred.

Nor can a sabkha setting be invoked without reservation. Such an interpretation can not be based on the mere presence of displacive evaporite pseudomorphs. A marginal marine sabkha *may* be an appropriate model for parts of the Lady Loretta Formation, but this is only substantiated with supporting sedimentological data and information about sedimentary facies architecture as discussed in the following Chapter.

Chapter 10 - Environments of Deposition, Sedimentary Architecture and Sequence Stratigraphy

10. ENVIRONMENTS OF DEPOSITION, SEDIMENTARY ARCHITECTURE AND SEQUENCE STRATIGRAPHY

10.1 FACIES AND ENVIRONMENTS OF DEPOSITION

10.1.1 Regional Setting

In a broad sense, the environments of deposition of the Lady Loretta Formation are constrained by the underlying Esperanza Formation and the overlying Shady Bore Quartzite and by laterally equivalent formations now thought to be contemporaneous (*i.e.* Fickling Group to the north, the upper Mount Isa Group to the south east and the Mussellbrook Formation to the north northwest).

The high relief microbialites of the Esperanza Formation were interpreted as subtidal. The intervening argillaceous and mixed carbonate/siliciclastic facies in the east were thought be intertidal and the sandstones south of Kamarga Dome were interpreted as high-energy river channels or barrier islands (Hutton and Sweet, 1982). Sami *et al.* (1997) described the Esperanza Formation as a southeast-facing, drowned, rimmed carbonate ramp. Several authors have noted that the transition to the Lady Loretta Formation is defined by a relatively sharp decrease in microbialite relief and abundance.

The arenaceous facies of the Shady Bore Quartzite have been interpreted as high energy beach, lagoonal and other marginal marine deposits (Hutton and Sweet, 1982; Hutton and Wilson, 1984). Bradshaw *et al.* (1996b) recognised marine, prodeltaic and fluvial facies in the Shady Bore Quartzite in the Brenda Creek to Police Creek area. A major fluvial incision was interpreted by Krassay *et al.* (1997) at Freemans Creek (located on Figure 3-5). On the basis of the thickness variations in the Shady Bore Quartzite, these fluvial, marine shoreline, lagoonal and paralic environments were postulated to have developed in an arc around an emergent landmass west of Lady Loretta mine (Hutton and Sweet, 1982).

Hutton and Sweet (1982) suggested that the Lady Loretta Formation is, in part lithostratigraphically, equivalent to the Walford Dolomite and Mount Les Siltstone in the Fickling Group to the north. McConachie and Dunster (in press)* interpreted seismic data to suggest that this relationship is complicated by thinning and onlap of the Lady Loretta Formation in the subsurface to the north. If any coeval package exists in the Fickling Group, it is likely to be microbial facies and ooid grainstones of the Walford Dolomite.

The upper Mount Isa Group, part of which is believed to be coeval with the Lady Loretta Formation, has been interpreted as the depositional record of a large saline-lake complex (Neudert, 1983). However, much of the group was regarded as deep marine by Southgate (pers. comm., 1997). On the basis of the similarity of the gamma signatures and the inferred changes to water depth, McConachie and Domagala (1997) tentatively correlated the Ore Sequence Equivalent in the Big Syncline with the ore equivalent horizon in the Urquhart Shale at King Gully near Mount Isa. As Southgate *et al.* (1997) pointed out, this may not be a valid chronostratigraphic correlation, because SHRIMP ages can be interpreted to suggest that the Paradise Creek Formation, not Lady Loretta Formation, is coeval with the Urquhart Shale. However, given the error bars on the ages (see Figure 3-1), either alternative is possible.

Part of the Mussellbrook Formation in the Carrara Range near the Northern Territory - Queensland border (Figure 3-2) may be the clastic basin-edge facies equivalent to the Lady Loretta Formation (Hutton and Sweet, 1982). Some of the lithologies described can be interpreted as fluvial and/or alluvial and subaerial deposits (Sweet, 1985). McConachie and Krassay (1997) suggested that the Lady Loretta Formation correlated with recessive siltstones and shales and brecciated microbial chert beds at Carrara Range.

Thus, the overall motif for the Lady Loretta Formation, as defined by the surrounding formations, is an overall regression from the relatively deep marine conditions over a large area to a beach/fluvial complex in the west and possible subaerial deposits in the far northwest.

10.1.2 Environments of Deposition in the Lady Loretta Formation

Within the Lady Loretta Formation, itself, the sedimentary facies are defined on the basis of the lithological, microbial and sedimentary features that correspond to a particular environment of deposition. These criteria are summarised in Table 10-1 and discussed in the following sections. Although presented in this way, the environments of deposition were not interpreted solely on the basis of individual facies. There also has to be both horizontal and vertical consistencies in keeping with Walther's Law.

10.1.3 Wavebase Facies

The deepest water facies preserved within the Lady Loretta Formation are shales and massive to faintly laminated, argillaceous dolostones. Both these lithologies are associated with subordinate fine grained tabular bedded argillaceous sandstones.

Rare outcrops of shale at Kamarga Dome weather to a distinct purple colour and can be traced along strike for several kilometres on air photos. The argillaceous lithologies are mostly recessive but have been RAB drilled and some can be mapped using airborne EM images. These shales are pyritic and locally high in TOC. Although the majority are strongly reduced, sulphides are not known to be abundant. The few samples available for study contain euhedral and vein pyrite that formed late in diagenesis. The only microbialites associated with the shales are prone microbial mat. There are few sedimentary structures within the argillaceous facies; rare small scale slumps and poorly developed distal Bouma sequences are present locally.

The deep water carbonates tend to more silty and argillaceous than most of their shallow water equivalents. Lamination and bedding, where present, commonly define crude stacked fining-up couplets. Other beds of carbonate several metres thick are internally featureless. These deep water carbonate lithologies are quite widespread and occur sporadically along strike at particular stratigraphic levels. The associated microbialites are either rare prone microbial mat or columnar conical biostromes. Some of the highest-relief, vertical non-elongate columnar conical microbialites in the Lady Loretta Formation occur associated with these deep water facies. A similar association has recently been demonstrated from the underlying Esperanza Formation (Sami *et al.*, 1997). Although these microbialites occur repeatedly at several stratigraphic levels, the *Conophyton*-like forms from the Lady Loretta Formation are generally lower in relief and much more limited in areal extent than the *Conophyton* biostromes and bioherms in the Esperanza Formation.

The deep water sandstones have abundant clay matrix and contain hummocky and swaley cross-stratification indicating deposition between fair-weather and storm wavebases.

The argillaceous and sandy facies are commonly recessive and easily overlooked. They rarely exceed 50 m in thickness in the north and account for only a small proportion of the total outcrop of the formation. Their distribution in the south is largely unknown because of the lack of outcrop.

10.1.4 Shallow Subtidal to Tidal Carbonate Facies

The shallow subtidal to tidal facies are most easily identified in the carbonate dominated lithologies in the north, where they are manifest as ooid shoals, storm-generated plate breccias and a variety of microbialites, some of which formed biostromes and bioherms with a maximum synoptic relief of about 1 m. These higher relief microbialites are commonly elongate and/or inclined with respect to the dominant palaeocurrent directions. This is interpreted to reflect wave action and tidal surge. The ooid grainstones are rarely laterally persistent along strike for any more than a few hundred metres, are typically between 0.3 and 1.0 m thick and are internally crossbedded. These are interpreted as ooid shoals that developed in shallow open-water wave-agitated conditions.

10.1.5 "Reef" Facies

The "reef" facies within the Lady Loretta Formation are dominated by some of the highest relief bioherms and biostromes, that commonly contain a vertical gradation from one microbial morphology to another, *e.g.* domes to cones. These build-ups are typically a few tens of metres across and persist along strike for several hundred metres, rarely up to a kilometre. Some of the smaller build-ups appear to be crescent-shaped in plan view. The "reef" facies are only known from sporadic locations on the Mount Oxide and Lawn Hill 1:100 000 maps. Elongation and inclination of individual microbialite elements and of the whole build-up are very common. Flanking debris aprons, internal pockets of angular debris between build-ups, and channels through the "reefs" were also observed. These microbial build-ups may have constituted a local barrier to form areally restricted rimmed shelf facies similar to the more extensive occurrences envisaged for parts of the Esperanza Formation. Argillites, carbonate breccias, laminated carbonates and sandstones were deposited between the "reefal" build-ups.

10.1.6 Lower Intertidal Facies

The lower intertidal facies of the Lady Loretta Formation are commonly clastic-dominated at

ENVIRONMENT	Supratidal/ Sabkha	Upper Intertidal	Beach/ Strandline	Channel	Lagoon on Upper Tidal Flat	Carbonate Lagoon	Lower Intertidal	Shallow Subtidal to Tidal Carbonate	"Reef"	Wavebase
DEPOSITIONAL PROCESSES	fluvial, emergence runoff, storm, erosion	alt. suspension & bedload In tidal, emergence runoff, storm	tidal	bedload, fluvial	variable energy, settling from suspension, current, storm	low energy, limited tidal influence, carbonate ppt, current, storm	current and wave, storm, bedload dominant	wave, storm	carbonate ppt, current and wave, storm	suspension, storm
SEDIMENTARY STRUCTURES	terrigenous pebbles, mudcracks	lenticular bedding, trough and herringbone crossbeds, reactivation surfaces, combined flow ripples, double crested and planed ripples, load casts, convolute bedding, tidalites	herringbone crossbeds, reactivation surfaces, interference ripples, tidalites	current ripples, crossbeds, graded beds, lenticular intraclast breccia	laminated to thin bedded, flanking terrigenous pebble pavement	oncoids, ooids, aggregate grains	flaser and lenticular bedding, interference, planed & double crested ripples, imbricated plate breccias, shrinkage cracks, water-escape structures, gutter casts, imbricated plate breccia, tidalites	imbricated plate breccia, ooid shoals	debris aprons, channels between bioherms	hummocky cross-stratification, laminites, turbidites, slumps
BIOGENIC STRUCTURES	none	laminites	none	none	laminites, some low relief microbialites	some microbialites	some low relief microbialites	biostromes & bioherms	biostromes & bioherms	rare columnar conical, laminites
EMERGENCE	microkarst	washout rills, runnels and microdeltas	washout rills, scour pits	rarely preserved	rarely preserved	rarely preserved	rarely preserved	none	none	none
DESICCATION/ SYNAERESIS	mudcracks, tepees	mudcracks, synaeresis	rare synaeresis	none	peripheral mudcracks, synaeresis	peripheral mudcracks	rarely preserved	none	none	none
EVAPORITES	halite, nodular & enterolithic gypsum/ anhydrite	strong halite & sulphate overprint	halite	?rare halite	minor peripheral halite & sulphate overprint	peripheral halite & sulphate overprint	halite & sulphate overprint	minor sulphate overprint	sulphate overprint from overlying units	none
CARBONATE/ SILICICLASTIC	mainly siliciclastic	intermixed / transitional	siliciclastic	mainly siliciclastic	mixed / transitional	mainly carbonate	mixed and transitional	variable north to south	mostly carbonate	argillaceous, minor carbonate
DOMINANT LITHOLOGIES	red-bed siltstones, thin bedded argillaceous dolostone	wavy bedded carbonates and clastics, granule conglomerate	strandline sandstone, well sorted quartzite	labile sandstone	highly carbonaceous variably dolomitic argillites	laminated carbonates	sandy siltstone, sandstone, wavy bedded	carbonate dominant, intraclast and rip up breccias, ooid grainstone	boundstone, grainstone, debris aprons, argillites between bioherms	argillaceous clastics, widespread carbonaceous facies
OXIDISED/ REDUCED	strongly oxidised	alt. oxidised/ reduced	oxidised	mixed	reduced	mixed	mixed	reduced	reduced	reduced
Fe SULPHIDE MORPHOLOGY	minor displacive cubic	displacive cubic & laminar replacement	rare cubic	none	mainly laminar bedded biogenic & replacement	rare displacive cubic on periphery	some laminar biogenic & replacement	rare	rare late	mostly non-bedded, sporadic laminar replacement

Table 10-1: Summary of facies and environments of deposition in the Lady Loretta Formation.

the base and mixed carbonate/siliciclastic at the top. The clastic lithologies show considerable lateral variation along strike. The lower intertidal facies are characterised by the dominance of flaser and wavy tidal bedding. Ripples are ubiquitous and commonly have modified crests and/or display interference patterns. Tidalites and storm deposits have been recognised. Shrinkage cracks and water escape structures commonly occur associated with an evaporite overprint. Prone and low relief microbialites are common locally.

10.1.7 Channel Facies

Clastic channel facies are recognisable by the characteristic morphology and ubiquitous trough crossbedded sandstones with unimodal palaeocurrent directions. They are not very common in the Lady Loretta Formation and were only recognised in some northern sections. In some cases, the channel contains a basal lag, graded beds of labile sandstone and current ripples.

10.1.8 Lagoonal Facies

Two types of lagoonal facies are recognised in the Lady Loretta Formation. Carbonate-dominated lagoons appear to be restricted to the northern areas of outcrop; whereas relatively small lagoons dominated by argillaceous, carbonaceous and pyritic sediments occur sporadically throughout the lithostratigraphy. Although individual examples are quite small, the argillaceous, carbonaceous and pyritic lagoonal facies occur over a much larger area geographically than carbonate-dominated lagoons.

Carbonate Lagoonal Facies

Carbonate lagoonal facies have been interpreted at Kamarga Dome on the basis of the similarity of facies associations to that of modern carbonate lagoons and the interpretation of the surrounding lithologies.

Argillaceous, Carbonaceous and Pyritic Lagoonal Facies

These are the most important facies in the Lady Loretta Formation from an economic perspective since they host the only significant SSHBM mineralisation discovered to date. Such lithologies have been the target of much of the previous exploration in the Lady Loretta Formation and are now recognised near the base of the formation at Johnson Creek, near the middle of the formation at Mellish Park and in the upper two thirds of the formation at Carrier and in the Lady Loretta to Tom Cat area. The areal distribution of each of these occurrences is less than 5 km^2. The thickness of lagoonal and peripheral facies is usually less than 100 m, with the subaqueous lagoonal sediments commonly restricted to a few tens of metres. As shown on the interpreted section for the Greater Loretta Syncline (Appendix A-15) and the Carrier area, pyritic, carbonaceous lagoonal facies may have developed locally more than once, with the economic mineralisation confined to only one of these packages.

These lagoonal lithologies are dominated by thin bedded to laminated, highly carbonaceous argillites, dolomitic siltstones and diagenetically altered Fe- and Mn-rich carbonates. Thin beds of fine grained sandstone and bedded pyrite are ubiquitous. Locally, pyrite may constitute over 50% of the beds by volume. Although dominated by plane parallel lamination; current ripples, wave ripples with opposed chevron-upbuilding and bimodal-bidirectional palaeocurrent directions have been recorded from the mine stratigraphy. Much of the bedded pyrite at the Lady Loretta mine has been interpreted as prone microbial laminite. Inclined elongate minidigitate microbialites have been documented from the southeastern edge of the inferred lagoon.

The S isotope data from the vicinity of the mine are consistent with a restricted marine setting, rather than a closed lacustrine basin (McGoldrick *et al.*, 1995).

The argillaceous pyritic lagoonal facies at the mine and at Carrier (Berg, 1986) contain a locally strong sulphate evaporite overprint. Desiccation and synaeresis cracks occur in the peripheral facies at the mine.

Modern and Holocene Analogues

Approximately 13% of the present coast line worldwide is lagoonal with modern lagoons developed behind barrier islands, reefs, ooid shoals, sand bars or carbonate mud mounds (Reading, 1978). The premises that a barrier of this type is essential to the definition of a lagoon and that a lagoon has to maintain an open-water conduit to the sea are semantic (Emery and Stevenson, 1957; Fairchild and Herrington, 1989; Gary *et al.*, 1973; Phleger, 1969). Many modern coastal lagoons (including some of those discussed below) are developed on, and separated from the sea by, a band of tidal flat sediments and thus lack a discernible barrier (*sensu* Reading, 1978). Many modern coastal lakes are lagoons in which the barrier has closed the opening to the sea. Variations of modern lagoons are also termed lagoonlets, swamps, pools, marshes, ponds and salinas. These terms have connotations of areal extent, water depth, vegetation and salinity. The present study has avoided such terms for Proterozoic analogues and uses the term lagoon in a loose sense in accordance with Gary *et al.* (1973).

It can also be argued that modern lagoons may be poor analogues for those developed in the absence of ice caps (as may have been the case during the Palaeo-proterozoic). During such periods, large areas are believed to be covered by epeiric seas and lagoons may have been considerably larger than any present day equivalents, especially on a low-gradient carbonate platform or rimmed shelf.

Modern lagoons show a great diversity of size, salinity and sediment composition due to differences in climate, aridity, fluvial input and tidal range (Reading, 1978). Those analogous to the argillaceous, carbonaceous and pyritic lagoonal facies of the Lady Loretta Formation include Langebaan Lagoon, South Africa; Lago Pueblo on the island of Gran Roque off Venezuela and parts of Laguna Madre, Texas.

Langebaan Lagoon is a good example of a mixed carbonate/siliciclastic lagoon developed in a hot arid climate and has been well documented by Flemming (1977). The water body is about 40 km^2; elongate, with a length of about 15 km; and is a maximum of 17 m deep. The lagoon is connected with the sea by a channel through a 1.5 km wide "barrier" of semi-consolidated Pleistocene and Holocene coastal sediments. Tidal flow in the lagoon is semidiurnal and slightly asymmetric. Surface water temperatures reach 30°C, compared to 16°C in the nearby ocean, and the lagoon is seasonally more saline than the sea. The lagoon and peripheral sediments are dominated by carbonate (most of bioclastic derivation) and sandstone derived from the reworking of the barrier complex. Argillaceous facies are restricted to the sheltered southern and western sides of the lagoon but dominate in the flanking salt marsh. This saline flat replaces the extensive mudflats that typically surround coastal lagoons elsewhere. There are some features in common with each of the lagoonal facies in the Lady Loretta Formation (Flemming, 1977). The general absence of argillaceous lithologies and the dominance of carbonate and mixed carbonate/siliciclastic facies in the lagoon itself is similar to the carbonate-dominated lagoonal facies of the Lady Loretta Formation. In particular, wave ripple morphologies studied in detail by Flemming (1977) are almost identical to those in similar grainsizes from the mixed carbonate/siliciclastic lagoonal facies of the Lady Loretta Formation. Much of the sediment on the lagoon floor, where a high rate of sediment movement precludes burrowing organisms, preserves parallel planar lamination and stacked fining-up couplets with rare current features. Flemming (1977) noted that the lower intertidal facies on the edge of the lagoon contained only rare wave and current generated bedforms and that much of the original lamination was being destroyed by bioturbation. The upper intertidal facies are characterised by numerous physical structures such as symmetric and asymmetric wave ripples, washout rills and small scale slump features.

The modern Lago Pueblo is a periodically density-stratified lagoon and has been described by Sonnenfeld (1976) and Sonnenfeld *et al.* (1977). The climate is semi-arid. Water depths vary seasonally between 60 cm and 1 m, with a maximum of 5 m and the total water-surface area is less than 1 km^2. Lago Pueblo is noteworthy because of its geochemistry. The stratification of the water column and solar heating results in a five fold enrichment of elements such as Mg, Na, K and Mn in the deeper waters. Fe is also concentrated but Pb, Zn and Cu are depleted relative to the surface water. High concentrations of organic matter, derived from algal mats, are being deposited and preserved within the accumulating sediment. This organic matter contains an average of 3.5% Fe, 1.0% Zn and anomalous concentrations of Mn, Cu and Pb. There are strong positive correlations between TOC in the mud and metal concentrations. Gypsum is being precipitated as large bladed crystals within the algal mat and as smaller crystals within the sediment. The lagoon floor sediments were described as thin bedded graded couplets and well laminated mixed carbonates and argillites. Algal mats were found to contribute to the lamination of the resulting sediment (Sonnenfeld, 1976; Sonnenfeld *et al.*, 1977).

Laguna Madre is commonly cited as an analogue for ancient lagoons formed in a semi-arid climate. The water body at Laguna Madre is linear and over 200 km long with a total drainage area of 1600 km^2. There are no major rivers entering the lagoon and seasonal freshwater influx from ephemeral streams is minimal. About half of the total area is termed mudflat and exposed during low water. A flanking sabkha has also been intensively studied (see Section 10.1.11). The average water depth is about 1 m; the lagoon is tidal but there is no periodic tide because the effects of wind are greater than the tidal influence. Salinity ranges from normal seawater to twice that (Kerr and Thomson, 1963). Laguna Madre is separated from the sea by a barrier island. The sedimentology was comprehensively documented by Rusnak (1960b) who described the bulk of the Holocene deposits as consisting of subgreywacke and subarkosic sand derived from the barrier island and deposited as a washout-over fan. Locally significant concentrations of limestone, gravel and relatively pure clay (>75% clay fraction) were noted. The argillaceous lithologies were described by Rusnak (1960b) as regularly layered and medium to thin bedded and are most abundant in the relatively deeper water where sedimentation is dominated by settling from suspension. Cores showed that at least tens of metres of these argillites had accumulated on the floor of the lagoon. Shepard (1960) described algal mat that caps some of the argillaceous lithologies causing "stagnant conditions and the production of H_2S and black colours underneath." Pyrite formation in these reducing sediments was described briefly by Cromwell *et al.* (1987). Laguna Madre is also often cited in the geological literature because of the ooids that form around part of the edge of the lagoon (see references in Chapter 6).

Van Loon and Wiggers (1975) described the sedimentology of a Holocene coastal lagoonal sequence from the Dutch coast that was comprised of "anoxic" clays and silts showing mostly fine parallel lamination and fine grained sand/mud interlayered bedding with sequences of wavy bedding and wave ripples. Minor iron sulphide was noted from the argillaceous lithologies.

In summary, Holocene to modern lagoons provide analogues for both the carbonate-dominated and the argillaceous, carbonaceous and pyritic facies in the Lady Loretta Formation. It is also interesting that the bottom sediments in modern, very shallow, stratified coastal lagoons can accumulate percent levels of metals as a result of organic activity.

Ancient Analogues

Numerous studies of Proterozoic sediments have invoked a coastal lagoon as a depositional setting and several have similarities to the carbonaceous, pyritic lagoonal facies inferred in the Lady Loretta Formation. The Proterozoic Bijaigarh Shale in India is a highly pyritic carbonaceous shale, 60 m thick, associated with fine grained sandstones and flanked by shallow marine deposits. The shale is so high in TOC that it was originally described as "coal" and there is sufficient bedded pyrite to be mined at several locations including the Amjhor deposit. Singh (1980) interpreted the host sediments as having been deposited in one of a series of lagoonal deposits on tidal flats and overlain by a transgressive sandstone shoal complex. The lagoon postulated for the Bijaigarh Shale would have been an order of magnitude larger than that proposed for the carbonaceous pyritic lagoons of Lady Loretta Formation.

Another example from the Proterozoic of India is the Ganurgarh Shale. It is one of several shale packages interbedded with argillaceous carbonates and underlain and overlain by sandstone. The lower 12 m of the 22 m that constitute the formation consists of laminated silty pyritic shale and siltstone with minor silty sandstone, commonly as lensoidal beds. Akhtar and Srivastava (1976), who described the geology of the shale, also studied ripple morphology in detail. They identified small symmetric and interference wave ripples with bimodal-bidirectional palaeocurrent directions. Mudcracks were noted in the peripheral facies. The shale was interpreted as having been deposited in a lagoon on a tidal flat, possibly developed behind a sand beach ridge (Akhtar and Srivastava, 1976).

The Proterozoic Canyon and Spiral Creek Formations on Ella Island (off Greenland) are another ancient sequence that has much in common with the Lady Loretta Formation. Fairchild and Herrington (1989) described mixed carbonate/siliciclastics and carbonates including imbricated plate breccias and gutter casts, thin ooid beds, anhydrite pseudomorphs, locally abundant microbialites with synoptic relief, and bituminous pyritic siltstones associated with films interpreted as subtidal microbial mats. This overall "tempestite-stromatolite-evaporite association" was interpreted as having been deposited in a shoreface-lagoon barred by high-relief microbialites that developed as a ramp evolved into a rimmed shelf.

10.1.9 Upper Intertidal Facies

The mixed carbonate/siliciclastic upper intertidal facies of the Lady Loretta Formation are characterised by lensoidal and lenticular tidal bedding, moderately high angle (10º to 20º) bidirectional trough-shaped sets formed by currents from the northwest and southwest, herringbone cross-stratification and reactivation surfaces, interference ripples and ripples with modified crests, tidalites, load casts, convolute bedding, desiccation cracks and synaeresis cracks. This facies also has a strong evaporite overprint. The microbialites are most commonly prone microbial laminites. These are associated with rare low-relief domal, cumulate and undulatory domal forms.

10.1.10 Beach / Strandline Facies

The beach and clastic strandline deposits of the northern Lady Loretta Formation are typically crossbedded well-sorted sandstone with some parallel lamination and wedge-shaped sets. Herringbone and trough cross-stratification, reactivation surfaces, and opposed palaeocurrent directions are diagnostic. Bimodal coset thickness and forset dip angles are features of some of the crossbeds. Smaller scale sedimentary features include interference ripples, washout rills and scour pits.

10.1.11 Supratidal / Sabkha Facies

The features considered diagnostic of a supratidal/sabkha setting in the Lady Loretta Formation are:

- subtidal and intertidal sediments that contain abundant widespread pseudomorphs of displacive cauliflower cherts and enterolithic anhydrite indicating that they have been elevated into the capillary zone of a saline flat
- widespread red-bed siltstones, as at Trent

- evidence of subaerial exposure such as mudcracks
- association with halite pseudomorphs.

Since the evaporite textures typical of a sabkha are an overprint of previously littoral sediments, the sabkha setting is only indicated by the evaporitic textures on the graphic logs in Appendix A-15.

10.2 RATES OF DEPOSITION AND FACIES ARCHITECTURE

10.2.1 Rates of Deposition

Estimation of rates of deposition in the Lady Loretta Formation is hampered by the lack of chronostratigraphic control, but some speculation is possible. The best available control is using the SHRIMP ages of 1647±4 Ma for the Lady Loretta Formation near the Ore Sequence at Lady Loretta mine and 1653±7 ma for the Paradise Creek Formation adjacent to Mount Gordon Fault Zone (as shown in Figure 1-3). It should be noted that the precision on these dates cannot preclude synchronisity, but if the analytical errors are ignored, one can assume a 6 Ma age difference. These locations have a present lateral separation of 29 km and, allowing for some thinning of both formations to the east, the two stratigraphic levels are separated by a minimum of 1500 m that includes the Esperanza Formation. After correcting for 40% compaction, this equates to a minimum depositional rate of 350 Bubnoff ($m/10^6$ yr). If the tuffs sampled near the Mount Gordon Fault are temporal equivalents of those in the basal Paradise Creek Formation south of the mine, there may >2200 m vertical separation. This equates to >513 Bubnoff.

In comparison, the average long-term depositional rate for present shallow carbonate platforms, using the same compaction factor, is 1400 Bubnoff (Einsele *et al.*, 1991). Data for modern tropical shelves (excluding reefs) presented in Enos (1991) range between about 250 and 2400. Thus, the rates of deposition for this portion of the McNamara Group are within the range of modern tropical shelves but may be less than the average modern carbonate platform. This may be explained by the relative lack of detrital skeletal debris on Proterozoic platforms.

10.2.2 Non-Random Sedimentation and Shallowing-Up Cycles

The Lady Loretta Formation contains numerous examples of apparently non-random sedimentation at various scales. Markov analysis and Fischer plots were used to demonstrate non-random sedimentation in the Cyclic Unit above the ore zone at Lady Loretta mine and in metre-scale peritidal bedding in Amoco 83-5 (Appendix A-10). Non-random changes to bed thickness have been documented from tidalites at a variety of scales (Appendix A-10.4). In addition, apparently cyclic, peritidal shallowing-up sequences, each about a metre thick, occur in the carbonate-dominated facies at Kamarga Dome.

Apparent "cyclic" sedimentation is well documented in the literature. Examples of different types of cycle, possibly relevant to the present study, have been variously referred to as punctuated aggradational cycles (Goodwin and Anderson, 1985), metre-scale allocycles (Anderson and Goodwin, 1990), shallowing-up, brining-up, shoaling-up or sabkha cycles. Pratt *et al.* (1992) deliberately avoided using the term "parasequence" to describe these cycles whereas several subsequent publications (*e.g.* Adams and Grotzinger, 1996) regarded shallowing-up carbonate cycles as synonymous with parasequences. Irrespective of the terminology used, an "ideal cycle" is typified by a basal subtidal unit, an intermediate intertidal facies and an upper supratidal unit with or without a terrestrial horizon at the top (Pratt *et al.*, 1992). Not all these elements will be present in every cycle and some may contain an evaporite overprint.

The means of pattern recognition, the mathematical basis and the sedimentological and sequence stratigraphic interpretations of such apparently non-random sedimentation are the subject of considerable debate in the literature. In particular, the long-standing text-book interpretations of metre-scale shallowing or brining-upward cycles (*e.g.* James (1979) and Pratt *et al.* (1992)) have been challenged in numerous papers by Drummond and Wilkinson (1993a-c, 1996) and Wilkinson *et al.* (1996). The following discussion presents the "classic" interpretation of each example of non-random sedimentation from the Lady Loretta Formation and a brief discussion of the opposing views.

Cycles in Drillhole Amoco 83-5

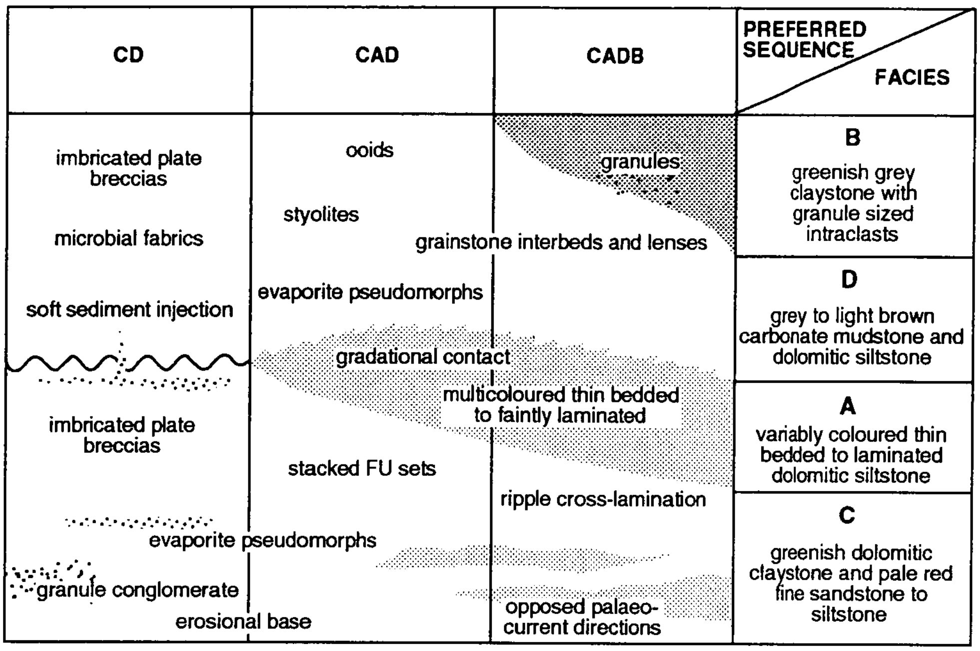
Four lithofacies, as described in Figure 10-1a, were recognised in the lower portion of the Lady Loretta Formation intersected in drillhole Amoco 83-5. An interval of *ca.* 100 m was analysed using Markov analysis and Fischer plots (Appendix A-10) to demonstrate non-random sedimentation and to infer the statistically preferred repeat sequence. The ideal cycle of lithofacies is C→A→D→B. However, not all elements are present in every cycle and the abbreviated cycles C→D and C→A→D were also statistically justified. These metre-scale cycles are interpreted to be peritidal based on the oxidised lithologies, the presence of ooids, ripple cross lamination with opposed palaeocurrent directions, evaporite pseudomorphs and the intermixed clastic and carbonate lithologies. However, the precise depositional environments of the individual lithofacies cannot be unequivocally interpreted from core. Further detailed study of this unit in outcrop would be required to determine if the vertical arrangement of facies represents a "classic" shallowing-up cycle.

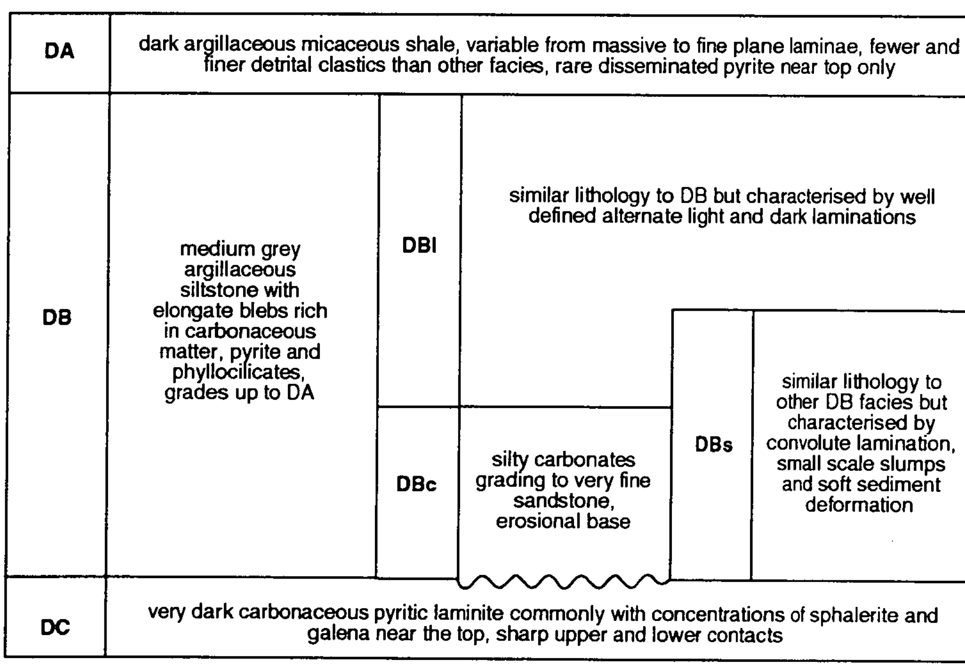
The Cyclic Unit at Lady Loretta Mine

The aptly named Cyclic Unit at the Lady Loretta mine consists of apparently regular decimetre to centimetre-scale alternation of up to six lithofacies recognised by Carr (1981) and described in Figure 10-1b. During the present study, quantitative stratigraphic analysis was undertaken of over 1700 bed-to-bed transitions from *ca.* 260 m of core of the Cyclic Unit in two drillholes. Data analysis using Markov analysis with normalised probability differences, the Wells (1989) method and Fischer plot analysis (Appendix A-10), all statistically confirmed non-random sedimentation. This statistically preferred sedimentary sequence ("modal cycle") is DC→DBv→DA→DC, where DBv includes DB and the laminated, "slumped" and carbonate variants recognised by Carr (1981). Not all lithofacies are present in every cycle and the various combinations of vertical arrangement, as determined statistically, are shown diagrammatically in Figure 10-1b. These are the same combinations as Carr (1981) recognised empirically.

Figure 10-1a: The statistically derived preferred sequence of lithofacies in a part of the core from drillhole Amoco 83-5. A "modal cycle" would consist of C→A→D→B. Not all elements are present in every cycle, giving rise to the variations shown along the top.

Figure 10-1b: The statistically derived preferred vertical arrangements of lithofacies in the Cyclic Unit at the Lady Loretta mine.


CD
CAD
CADB
PREFERRED SEQUENCE
FACIES
imbricated plate breccias
microbial fabrics
soft sediment injection
ooids
styolites
evaporite pseudomorphs
granules
grainstone interbeds and lenses
B
greenish grey claystone with granule sized intraclasts
D
grey to light brown carbonate mudstone and dolomitic siltstone
gradational contact
multicoloured thin bedded to faintly laminated
imbricated plate breccias
stacked FU sets
ripple cross-lamination
A
variably coloured thin bedded to laminated dolomitic siltstone
C
greenish dolomitic claystone and pale red fine sandstone to siltstone
evaporite pseudomorphs
granule conglomerate
erosional base
opposed palaeo-current directions


DA
dark argillaceous micaceous shale, variable from massive to fine plane laminae, fewer and finer detrital clastics than other facies, rare disseminated pyrite near top only
DB
medium grey argillaceous siltstone with elongate blebs rich in carbonaceous matter, pyrite and phyllocilicates, grades up to DA
DBl
similar lithology to DB but characterised by well defined alternate light and dark laminations
DBc
silty carbonates grading to very fine sandstone, erosional base
DBs
similar lithology to other DB facies but characterised by convolute lamination, small scale slumps and soft sediment deformation
DC
very dark carbonaceous pyritic laminite commonly with concentrations of sphalerite and galena near the top, sharp upper and lower contacts

The current study favours only minor modification to Carr's (1981) sedimentological interpretation of the Cyclic Unit. Carr (1981) interpreted the non-random sedimentation as resulting from both chemical and mechanical processes of sedimentation. The chemical deposition of pyrite and carbonate was cyclically interspersed with the sedimentary influx of argillaceous and carbonaceous detrital clastics. Carr (1981) stressed that the cycles were inconsistent with Bouma sequences since that term has connotations of repeated episodes of gravity-driven flow and excludes the background chemical sedimentation documented here.

A detailed description of deposition begins with pyrite, or more strictly a bedded microbial precursor lithology such as microbial mat (DC), as the steady state and the cyclicity is attributed to regular variations in the supply of sediment resulting from rapid increases and gradual decreases in the flow rate and/or volume of water entering a shallow basin. Each influx either scoured the substrate (DBc) and/or clouded the water sufficiently to kill the microbial mat. The unstable layer deposited during the influx could contain carbonaceous blebs (DB) from the underlying microbial mat and, as soft sediment, it could be deformed into convolute bedding and small scale slumps (DBs). As the water column gradually returned to normal, microbes within the water column produced a rain of microbial material. Initially, this was deposited as highly carbonaceous laminae interbedded with background carbonate precipitation (DBl). The microbial bloom eventually dominated sedimentation (DA) and microbial mat was re-established to start the next cycle. Carr (1981) noted a difference between the morphology of pyrite from DC (the bedded mat) and DBl/DA (the detrital rain). Although not stressed by Carr (1981), his data can also be interpreted to suggest that there is a corresponding difference in mineralisation throughout each cycle, particularly with respect to galena in the bedded pyrite and the fine grained sphalerite associated with pyrite in the beds of euhedral pyrite. This warrants further textural study.

Although Carr (1981) interpreted this cyclicity as evidence of very shallow water, the author contends that this is not necessarily the case. The processes he invoked, the thicknesses of individual cycles and the thickness of the Cyclic Unit as a whole could have occurred in almost any depth of water within the photic zone (tens of metres). Similarly, in the absence of any biostratigraphic or chronostratigraphic control, the mechanism that produced literally thousands of periodic (or episodic) influxes remains obscure. Periodic mechanisms could include a tidal influence or seasonal runoff. Episodic mechanisms include storm-generated inflow and turbulence. Both these mechanisms are interpreted to have influenced sedimentation throughout much of the northern Lady Loretta Formation, including presumably coeval lithologies.

Metre-Scale Shallowing-Up Peritidal Cycles at Kamarga Dome

Empirical observation suggests that much of the exposed carbonate and mixed carbonate/siliciclastic lithologies at Lily Lagoon and Kamarga Dome contain metre-scale cycles comparable to those documented from Proterozoic peritidal and shallow marine sequences elsewhere (*e.g.* Crevello, 1991; Grotzinger, 1989b: Sami and James, 1994;

Wright, 1992b).

Metre-scale examples from the Lady Loretta Formation include the upward transition from domal to conical microbialites, ooid grainstone to microbialite, silty and argillaceous carbonates to fine grained clastics with an evaporite overprint, and domal microbialites overlain by laminated and thin bedded carbonate or mixed carbonate siliciclastics. As discussed in Section 10.3.3, these cycles are not as laterally extensive as some other Proterozoic examples (*e.g.* Grotzinger, 1989b) and tend to form a complex mosaic as described from Cambrian carbonates by Adams and Grotzinger (1996). Most of these cycles in the Lady Loretta Formation can be interpreted as classic peritidal, lagoonal and/or subtidal shallowing-up cycles.

However, an opposing view of cyclic sedimentation in general, and peritidal cycles in particular, has developed from the geostatistical and sedimentological work of Drummond and Wilkinson (1993 *et seq.*). Most recently, Wilkinson *et al.* (1996) stated that "metre-scale cyclicity in many, if not most, epicratonic sequences is more apparent than real, that perceptions of repeated and eustatically driven platform flooding are largely incorrect, and that a substantial component of presumed metre-scale stratigraphic order in peritidal carbonates reflects little more than the random migration of various sedimentary environments over specific platform localities during long-term accumulation of peritidal carbonate." Such metre-scale "cycles" are currently widely regarded as parasequences and the important implications of this work for sequence stratigraphy will be discussed in the following section.

10.3 SEQUENCE STRATIGRAPHIC INTERPRETATION

10.3.1 Background

The concepts and techniques of sequence stratigraphy were initially developed by Exxon Research during the early 1980s as a refinement of seismic stratigraphy (Krapez, 1996). Sequence stratigraphic analysis treats stratigraphy as a framework of genetically-related strata bounded by chronostratigraphic surfaces of erosion, non-deposition or their correlative conformities. The underlying precept is that space for sediment accumulation must be created to enable deposition to continue and that this will be controlled by the interplay of the changes in sealevel, tectonic subsidence and sediment supply. These concepts were developed using the principles of terrigenous clastic sedimentation and have, in conjunction with seismic stratigraphy, proved to be a powerful tool for basin analysis and hydrocarbon exploration.

Most recently, sequence stratigraphic analysis has been applied to carbonates and mixed carbonate/siliciclastic successions. One of the important differences between carbonates and clastics is that thick sequences of carbonates can be chemically precipitated *in situ*. They are therefore capable of filling accumulation space or of keeping-up with rising sealevel independent of detrital input. This makes assignation of allo- versus autocyclic mechanisms very difficult (some would argue, impossible) in carbonate or mixed carbonate/siliciclastic systems (James and Kendall, 1992). Furthermore, the original Exxon carbonate sequence stratigraphic model implied similar substantial shedding of platform-derived unconsolidated sediment for both clastics and carbonates subaerially exposed during a lowstand. However, Dravis (1996) demonstrated that because of rapid subaerial lithification, carbonate platforms may actually shed most material during periods of inundation. Another important difference is that carbonate diagenesis can vary significantly from one sequence stratigraphic system to another (Wright, 1993).

Application of the sequence stratigraphic approach to the Proterozoic rock record is also a relatively recent development and has been described by Christie-Blick *et al.* (1988) McConachie and Dunster (1996) and Krapez (1996, 1997). In rocks of this age, the technique is limited by the lack of detailed biostratigraphic or chronostratigraphic control. This means that, without linking seismic data, correlation of sequences from one field section (or gamma log) to another is largely subjective. It is also debatable to what extent the time-frames commonly associated with the sequence stratigraphic component units (1st to 5th or 6th order sequences) in the Phanerozoic can be applied to the Proterozoic (*cf.* the opposing opinions of Krapez, 1997 and Drummond and Wilkinson, 1996). This posed practical difficulties in the recognition and correlation of sequence stratigraphic cycles during the present study as one can never be sure that sequences of the same time-frame are being correlated.

Some peritidal carbonate and mixed carbonate/siliciclastic sequences (as in the northern Lady Loretta Formation) can be very difficult to correlate using sequence stratigraphy. As demonstrated by Adams and Grotzinger (1996), constituent lithofacies may form a mosaic in which no elements are laterally persistent. Adams and Grotzinger (1996) found that intertidal facies interfinger laterally with subtidal facies, that peritidal facies capping shoaling sequences are not laterally continuous and that "most subtidal facies extend laterally for less than 300 m, passing gradationally (over tens of centimetres to metres) into other, laterally adjacent subtidal facies". Whereas many parasequences corresponding to "cycles" could be traced across the 1.8 km outcrop, other parasequences "do not extend laterally for more than a few hundred metres and are not distinguishable in a vertical profile from those that extend laterally for tens of kilometres" (Adams and Grotzinger, 1996). Gamma logs of the outcrop are not advantageous in this situation where there are few clay-rich intervals (Aigner *et al.*, 1995 - see Appendix A-12). The wide lateral spacing of sections in the peritidal facies of the Lady Loretta Formation also preclude unambiguous sequence stratigraphic correlations.

Work by McConachie and Dunster (1996)* demonstrated that a sequence stratigraphic analysis of seismic data could be used to identify the stratigraphic levels of potential epigenetic stratabound mineralisation in the area by predicting the geometry of suitable aquifers for the long distance migration of metal-bearing fluids and potential redox sites in trapping sedimentary rocks. Sequence stratigraphy may also be used to predict the types of fluid (marine, meteoric, vadose *etc.*) that is produced within each sequence and to what extent those fluids can influence the underlying sequence. This has implications for the possible fluid-mixing or direct migration of metal-bearing brines into the shallow subsurface as implicated in early epigenetic and syngenetic SSHBM mineralisation models.

Sequence stratigraphic analysis of the Mount Isa Basin succession has been based on a seismic data set from the northern flanks of the basin and extrapolated into the structurally-complex areas to the south using gamma ray logs from drill core and outcrop (see Bradshaw *et al.*, 1996).

10.3.2 Terminology and Methodology

This study of the sequence stratigraphy of the Lady Loretta Formation was based on the identification, in the field or in drillcore, of key bounding surfaces that correspond to rapid changes in water depth and hence delimit packages of genetically-related sedimentary rocks. A conventional sedimentary facies-based interpretation was used to infer changes to RSL within, and between, these packages. Theoretically, it should be possible to correlate such surfaces long distances independent of the lithofacies involved. Key surfaces and characteristic patterns and cycles can also be interpreted in the few available gamma logs. The technique is outlined in Krassay (1996) and Krassay and McConachie (1996) and discussed in Appendix A-12.2. In this sense, sequence stratigraphy has been used as a means of interpreting the stratigraphy, supposedly (but never truly) independent of lithology. This is in keeping with the opinions expressed by Posamentier and James (1993) and Trendall (1996). It is stressed that the following section is a first-pass interpretation based on the correlation of widely spaced measured sections, core descriptions and gamma logs and is attempting to interpret data at a smaller scale than the NABRE sequence stratigraphic studies (*e.g.* Southgate *et al.*, 1996). Any sequence stratigraphic interpretation, such as that presented here, that does not have recourse to seismic data and high resolution biostratigraphic and chronostratigraphic control cannot be presented as a rigorous analysis.

A brief introduction to the terminology of sequence stratigraphy is presented in Appendix A-12. The various system tracts and key surfaces recognised within the Lady Loretta Formation are shown on the interpreted graphic logs in Appendix A-15 and are described below.

Lowstand System Tracts

The proximal LST facies are regressive sequences dominated by tidal flat sediments, commonly interbedded with shallow subtidal or, less commonly, supratidal deposits. They may contain significant periods of non-deposition or erosion. The peritidal sediments are commonly cyclic. In some LSTs in the Lady Loretta Formation, the relative proportions of shallow subtidal facies decrease up-section as the proportion of thin tidal flat parasequences increase. Evidence of desiccation and exposure also increases upward through many of the parasequences. The parasequences also thin up-section in some cases. Thin sandstone lenses and channel deposits are commonest in the proximal LST facies and storm deposits such as plate breccias are preserved locally. In the carbonate-dominated and mixed-carbonate siliciclastic lithologies in the north, there is evidence of a strong evaporitic overprint in most LSTs. In exceptional cases, this overprint can extend down far enough to affect the underlying systems tract. During a regional regression that marks the base of a LST, extensive lagoonal facies develop over previously relatively deeper water facies. In many instances in the Lady Loretta Formation, LST lagoonal facies are deposited on the tidal flat as a result of smaller perturbations in RSL during the lowstand. These closely associated clastic intertidal facies would provide suitable conduits for the passage of fluids and could be implicated in mineralisation. Furthermore, the carbonates in the lagoonal facies of the Lady Loretta Formation are commonly interbedded with highly carbonaceous and bedded pyritic facies that would act as reductants. These carbonates also have a complex diagenesis and are typified by diagenetic enrichment in Fe and Mn. More-distal LSTs are typified by relatively thinner parasequences and a relatively higher proportion of subtidal facies.

Transgressive System Tracts

TSTs result from the landward shift of facies during a transgression. Amalgamated subtidal units are common. In the mixed carbonate/siliciclastic facies of the Lady Loretta Formation, TSTs are characterised by poorly defined thickening-up parasequences, in which the proportion of subtidal facies increases upward. In argillaceous and other clastic-dominated lithologies, the parasequences generally fine-up and thin into the basin. Elsewhere, little sediment may have accumulated (or have been preserved) during the transgression and the corresponding TST will be relatively thin. Erosional surfaces and basal transgressive lags can only rarely be recognised and, as a result, many of the TSTs within the Lady Loretta Formation are poorly defined.

Highstand System Tracts

HSTs in the northern Lady Loretta Formation are typically prograding highstand coastal deposits and their equivalent offshore deeper water facies. Where they contain sandstone, these units generally thin upward. The most-proximal HSTs, in both the north and south, contain relatively thick shale-dominated lithologies that can be lithostratigraphically correlated for kilometres along strike and persist similar distances into the basin. These facies tend to be recessive and are only poorly documented, but appear to contain much less bedded pyrite than similar reduced argillaceous lithologies in the LST. On Kamarga Dome, the MFS shales are typically poorly outcropping and purple in colour.

The carbonate lithologies in HSTs are pervasively dolomitised and/or recrystallised, commonly have a higher argillaceous component, and tend to more thickly bedded and monotonous compared to those in other system tracts. McConachie and Dunster (1996)* suggested that the uppermost HST shales or carbonates in the northern Mount Isa Basin commonly contain trace late epigenetic mineralisation.

Transgressive Surfaces

By definition, a sequence stratigraphic transgressive surface (TS) marks the contact between the LST and the overlying TST. Such surfaces can best be identified sedimentologically in the Lady Loretta Formation where they correspond to the abrupt transition from upper intertidal facies to subtidal deposits. In practise, transgressive surfaces were difficult to identify in the field, particularly where the sequence is dominated by erosively-based storm deposits.

Maximum Flooding Surfaces

A distal MFS is typically a shale-prone, organic-rich, point of inflection between transgressive and regressive sequences. Proximal equivalents can be lagoonal argillites or carbonate capping a transgressive stacking pattern. Bradshaw *et al.* (1996) were of the opinion that "sediment-hosted mineral deposits in the Mount Isa Basin are usually found in black (organic-rich) shale and dolomitic siltstone ... closely associated with condensed intervals and maximum flooding surfaces." As explained in Appendix A-12.1, not all organic-rich shales in the Lady Loretta Formation have a high gamma response and not all shales in the Lady Loretta Formation are interpreted as deepest-water deposits.

Emergence Surfaces

Emergence surfaces (ES) occur most commonly near the landward edge of basins. They can best be recognised where they cap or truncate prograding cycles and correspond to the minimum inferred palaeo-bathymetry. In the Lady Loretta Formation, such surfaces are typified by sedimentological evidence of emergence such as scoured contacts, planed ripples or washout rills and are usually associated with a strong evaporitic overprint. Larger scale erosional or non-depositional contacts are difficult to recognise, especially in core.

10.3.3 Regional Sequence Stratigraphy of the Lady Loretta Formation

Sequence stratigraphic interpretations of selected measured sections (see Table 1-2) are included on the logs in Appendix A-15 and discussed below. The paucity of suitable outcrop, the lack of chronostratigraphic or seismic control, the difficulty in recognising and tracing key surfaces laterally, the peritidal nature of much of the sequence and the mixed carbonate/siliciclastic and transitional lithologies all mitigate against unambiguous regional sequence stratigraphic correlations within the Lady Loretta Formation.

Esperanza Formation to lower Lady Loretta Formation

The transition from the Esperanza Formation to the Lady Loretta Formation is undoubtedly a significant basin-wide event. This interpretation is based on the premise that a major change in the rate of change of accommodation space was responsible for the widespread demise of the high-relief microbialites that typify much of the upper-most Esperanza Formation. The interval immediately overlying the Esperanza Formation microbialites is poorly exposed and the available data away from the Lady Loretta ore body are summarised below.

The basal 260 m of the Lady Loretta Formation is partially exposed in the Thornton River section. This unit consists of mixed carbonate/siliciclastics with imbricated plate breccias, prone microbial laminites and a variety of microbialites with moderate to low synoptic relief. Cauliflower cherts occur at sporadic stratigraphic levels. Similar features are observed in the basal 80 m exposed at Mellish Park where the lithologies are carbonate dominated. The contact of the Esperanza and Lady Loretta Formations can be traced in outcrop around the edge of the Dayview Syncline and correlated to the core intersection in CM35. The lower-most 180 m tst of core of the Lady Loretta Formation shows a continuation of carbonate deposition with sporadic low-relief microbialites and rare thin ooid grainstone interbeds. There are no cauliflower cherts in this interval in CM35. The gamma log of CM35, shown on the graphic log, has no major inflections that would be interpreted as a major sequence boundary elsewhere. As previously discussed, the lower-most Lady Loretta Formation at Johnson Creek contains localised highly carbonaceous and pyritic facies analogous to the host rocks of the ore body.

These data cannot be unambiguously interpreted in terms of sequence stratigraphy. If this transition corresponds to an increase in the rate of creation of accommodation space coincident with a drowning it will, by definition, not be a major sequence stratigraphic boundary (unless there was no lowstand deposition at the site, which is considered unlikely if the basin was submerged during the lowstand - McConachie, written comm., 1997). However, if it represents a decrease corresponding to a widespread regression, the transition from Lady Loretta Formation would be a sequence stratigraphic boundary. For ease of reference, the surface corresponding to this change is termed I, but its sequence stratigraphic significance remains enigmatic.

Kamarga Dome Sections

Further up-section, sequence stratigraphic interpretations were made of selected outcrop sections in the Kamarga Dome area (Appendix A-15). These sections are only a small fraction of the Lady Loretta Formation at any one location, are spaced several kilometres apart, and include only a single gamma log of outcrop (Wangunda). Several of the deeper-water recessive shales that can be correlated between sections and traced on airphotos were interpreted as MFSs. However, the volumetrically dominant peritidal facies form a mosaic and many beds change in lithology over several hundred metres along strike. Establishing the relative significance of key surfaces as either parasequence or sequence boundaries proved problematic. In most cases, it was not possible to walk out interpreted parasequence and sequence boundaries between sections or to trace them on airphotos. Consequently, it is not prudent to attempt to correlate the widely spaced measured sections in detail.

These complications to a sequence stratigraphic interpretation reflect the highly variable nature of the peritidal facies in the northern Lady Loretta Formation. Such a mosaic of peritidal facies was documented in detail from the Cambrian by Adams and Grotzinger (1996) and contrasts strongly with the laterally extensive Proterozoic peritidal cycles described by Grotzinger (1986b) and the laterally extensive microbial facies in the Esperanza Formation. This may be interpreted to indicate that this portion of the northern Lady Loretta Formation was deposited in underfilled accommodation or moderate to low amplitude accommodation fluctuations during low-amplitude sealevel fluctuations as suggested by Adams and Grotzinger (1996). Detailed work at the scale undertaken by Adams and Grotzinger (1996) would be necessary to investigate the concept further, but it should be possible to relate the peritidal facies in the Lady Loretta Formation to the theoretical models described by Pratt *et al.* (1992). When the rate of creation of accommodation is low, peritidal LSTs and early HSTs would probably be aggradational and relatively thin. If the rate of change in accommodation space is high, TSTs would be characterised by relatively thick backstepping tidal flats' successions or relatively thin successions that offlap in a shingled fashion (late HST , early LST; Pratt *et al.*, 1992).

Upper-most Lady Loretta Formation to Shady Bore Quartzite

As explained in Section 3.2.10, the lithological contact between the Lady Loretta Formation and the Shady Bore Quartzite has been thoroughly investigated. This is because several authors (*e.g.* McConachie, 1993b) suggested that such a rapid and widespread change from carbonate-dominated to shallow water sandstone deposition must correspond to a fundamental change in basin dynamics with a marked basin-ward shift in facies and hence be a major sequence boundary. Indeed, McConachie (1993b) and Krassay *et al.* (1997) related the lithological contact to a major erosional truncation evident on the Comalco seismic data from the northern Mount Isa Basin. This warrants some comment based on the seismic interpretation and the field relationships seen in outcrop in the south.

The Shady Bore Quartzite thins to the north and east from the Russell Creek area and it is possible that it is not present over the area of the Comalco seismic grid (McConachie and Dunster, in press)*. It was not intersected in petroleum wells that were interpreted to have reached the equivalent of the top of the Lady Loretta Formation (Dunster et al., 1993a,b). The Shady Bore Quartzite has no lithostratigraphic equivalent in the Fickling Group, to which the Comalco seismic was tied (McConachie and Dunster, in press)*.

To describe the sequence stratigraphic surface interpreted on the seismic as the contact of the Lady Loretta Formation and Shady Bore Quartzite (*e.g.* Krassay *et al.*, 1997) could, therefore, be misleading, since the same sequence stratigraphic surface may separate the Lady Loretta Formation and ?Riversleigh Formation elsewhere. Furthermore, since many of the major sequence boundaries interpreted on the seismic grade basin-ward from erosional truncations to conformable relationships (and vice-versa), extrapolation of the detailed geometries seen on the seismic sections to outcrop relationships tens of kilometres to the south is speculative.

During the current study and the 1:100 000 government mapping, the field relationships between the Lady Loretta Formation and Shady Bore Quartzite were investigated in more than two dozen places and found to be either conformable or faulted. Typically, the transition is marked by thinning-upward laterally continuous stacked progradational cycles (Figure 3-6) that may be interpreted as a decrease in accommodation space probably due to filling of the basin. This lithological relationship was confirmed by NABRE sections at Mount Caroline, southern Kamarga Dome and Brenda Creek (Zeilinger, 1995; Bradshaw *et al.* 1996b). The only exception was documented by Krassay *et al.* (1997) from Freemans Creek, where a fluvial incision of Shady Bore Quartzite into the top of the Lady Loretta Formation was interpreted as corresponding to a major erosional sequence boundary between the Lady Loretta Formation and Shady Bore Quartzite.

The major sequence boundary, if it exists as predicted, could be intra- Shady Bore Quartzite and correspond to the change from marine and paralic sandstone to fluvial sandstone (as documented by Bradshaw *et al.* 1996b at Brenda Creek). The fluvial channel recognised by Krassay *et al.* (1997) could then be interpreted as an unusually erosive feature that removed the lower marine Shady Bore Quartzite.

10.3.4 Sequence Stratigraphic Correlations in the Vicinity of the Lady Loretta Mine

Detailed sequence stratigraphic correlations are possible in the vicinity of the Lady Loretta mine where the Pyritic Unit through to the Cyclic Unit have been intersected in numerous drillholes and relatively close-spaced gamma logs are available. In particular, the prospective interval is easy to correlate on gamma logs, indicating that this might be a useful adjutant to exploration within the local area.

As with the regional data, the sequence stratigraphic significance (or otherwise) of the I horizon that corresponds to the demise of the high-relief microbialites in the Esperanza Formation is open to interpretation. The pertinent observations are presented below. (Note that some of the Esperanza Formation near the mine and shown on Figure 3-7 was omitted from the published 1:100 000 Mammoth Mines Region geological map).

Adjacent to Western Border Fault, to the southeast of the ore body, the microbialites of the Esperanza Formation are overlain by *ca.* 80 m of laminated to thin bedded silicified dolostone and subordinate fine grained sandstone with tidal bedding. Small domal microbialites are rare. This package (mapped as a separate transition zone in Figure 3-7 and shown on the summary log of the Greater Loretta Syncline in Appendix A-15) is in turn overlain by a monotonous massive and thin bedded dolostone. To the north of the Carlton Fault Zone, the transition zone contains more ferruginous and argillaceous lithologies. In the absence of any other data, another horizon, II, is tentatively placed at the boundary of the mapped transition zone and the dolostone of the basal undifferentiated footwall sequence. Since a basin-ward shift in facies cannot be conclusively demonstrated, interpretation of II as a sequence boundary is speculative.

The sequence stratigraphic correlation of the overlying portion of the Lady Loretta Formation has been documented from outcrop in the Greater Loretta Syncline, a representative drillhole in each of the synclines and drillhole LA64 in the Tom Cat area to the northeast. The raw gamma data for 2240P142 and 0740P148 were presented in Zeilinger (1996). Figure 10-2 is the proposed sequence stratigraphic correlation, based on lithology, sedimentology, geochemistry and the gamma logs interpreted at 1:200 scale. Note that, although 13 key surfaces were correlated, only those specifically labelled are interpreted to have sequence stratigraphic significance.

The Ore Sequence and its lateral equivalents are bounded by two sequence stratigraphic horizons (XI and XII). This package can be traced as an equivalent gamma low in all three drillcores and correlates to a highly ferruginous chert in outcrop. The low gamma response in drillcore is somewhat surprising given the highly carbonaceous nature of the rocks and may reflect the abundance of pyrite (see Appendix A-12.1). That not withstanding, such a response is consistent with the sedimentological interpretation that this is a lagoonal package deposited during an overall lowstand. The gamma response is *not* consistent with the interpretation of the Ore Sequence as an organic-rich condensed sequence corresponding to a MFS (*cf.* Bradshaw et al., 1996b). Furthermore, independent work by McConachie (written comm., 1997) also identified and correlated the XI horizon as the sequence boundary at the base of a LST.

If the Ore Sequence and its equivalent are interpreted as a lowstand, either the X or the XI surfaces, about 50 and 25 m below the top of the Ore Sequence respectively, may be the sequence stratigraphic boundary separating the LST from the underlying HST.

The overlying packages are interpreted as an overall transgression to a MFS (XVII) about 90 m above the top of the Ore Sequence. This is manifest as an interval of relatively high total gamma count that can be correlated between all three drillcores. The actual surface is difficult to define within the zone of high gamma response and is shown tentatively in Figure 10-2. This zone also corresponds to the argillaceous interval at about 1120 m in the measured outcrop section of the Greater Loretta Syncline.

The sequence boundary that marks the top of the overlying HST may be as high as XXII. In which case, the basin-ward shift in facies of the LST is typified by the increase in arenaceous lithologies and the presence of ooid grainstone and halite pseudomorphs in outcrop.

The contact between the Lady Loretta Formation and the Shady Bore Quartzite is not present near the Lady Loretta mine, presumably because the Shady Bore Quartzite was eroded away before or during the Cambrian.

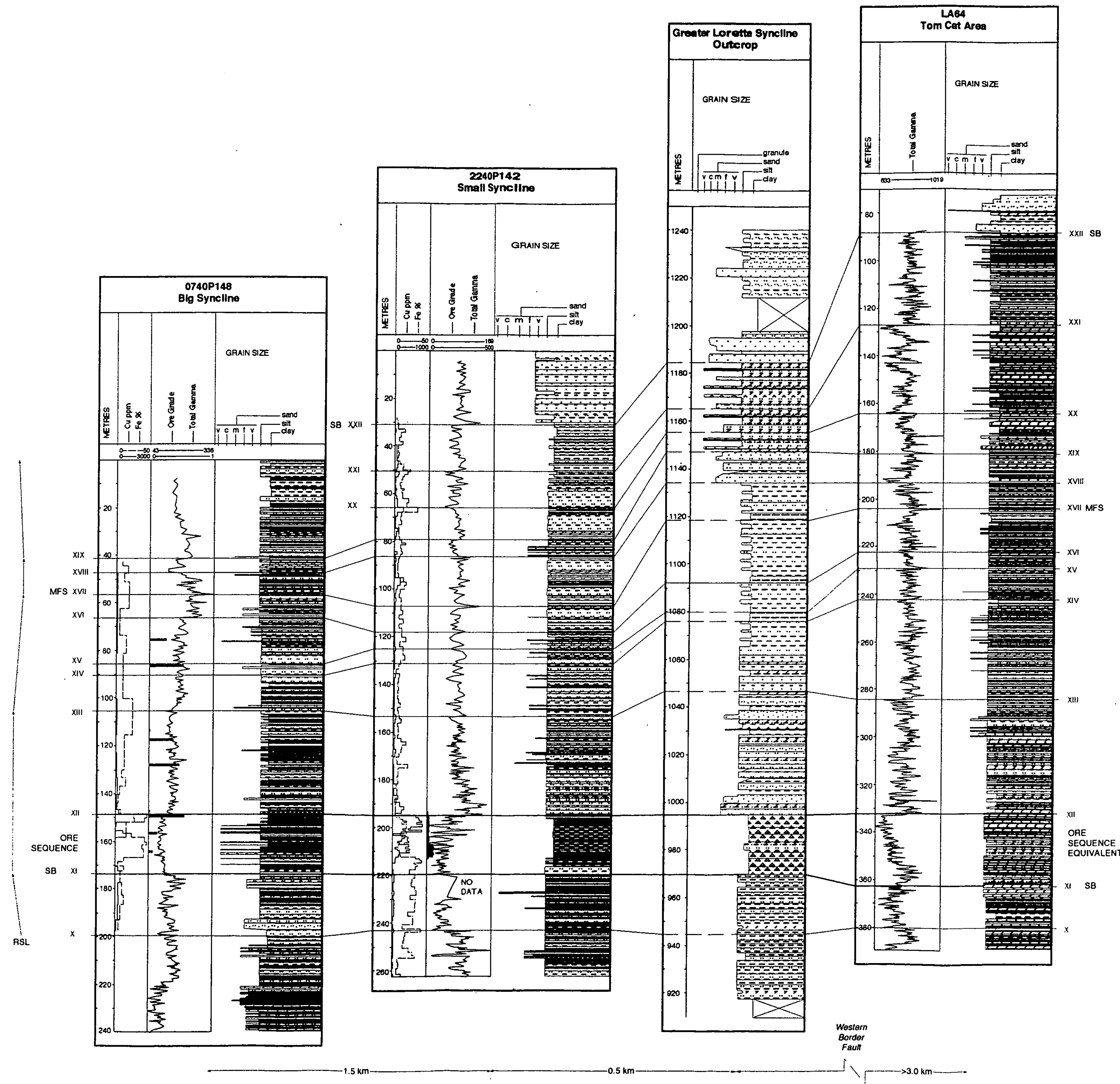
Summary and Discussion

In summary, the regional sequence stratigraphic understanding of the Lady Loretta Formation is still evolving. It is hampered by the lack of suitable outcrop at the site of a possible sequence boundary between the Esperanza and Lady Loretta Formations. The erosional unconformity that Krassay *et al.* (1997) related to a major sequence boundary between the Lady Loretta Formation and the Shady Bore Quartzite is not regionally sustainable on field evidence or on the interpretation of seismic data as tied to drilling. Quite detailed local sequence stratigraphic correlations are possible in the region of the Lady Loretta mine where data are available, but the same is not true of the peritidal carbonate facies at Kamarga Dome.

All the sequence stratigraphic interpretations presented here are preliminary because of the lack of adequate chrono- or biostratigraphic control.

If a conceptional regional sequence stratigraphic model can be developed for the Lady Loretta Formation, it should be possible to use it predictively to locate packages that are likely to contain potential SSHBM host rocks such as highly carbonaceous and pyritic shale and dolomitic siltstones, be they lagoonal or deep marine. Such a model is also contingent on identifying the shelf and ramp geometry.

Figure 10-2: Sequence stratigraphic correlation of the mine stratigraphy to the outcrop and to the Tom Cat area to the northeast. Only those horizons specifically labelled are interpreted to have sequence stratigraphic significance.



0740P148
Big Syncline
2240P142
Small Syncline
Greater Loretta Syncline Outcrop
LA64
Tom Cat Area
METRES
GRAIN SIZE
Cu ppm
Fe %
Ore Grade
Total Gamma
sand
silt
clay
granule
v c m f v
SB XXII
XXI
XX
XIX
XVIII
MFS XVII
XVI
XV
XIV
XIII
XII
ORE SEQUENCE
SB XI
X
RSL
NO DATA
XXII SB
XVII MFS
ORE SEQUENCE EQUIVALENT
XI SB
Western Border Fault
1.5 km
0.5 km
>3.0 km

10.4 SHELF AND RAMP GEOMETRY

Previous interpretations of the shelf and ramp geometry for the formations in the McNamara Group have advocated either rifts (at various scales) or variations of the Grotzinger (1989) models for carbonate platforms (Figure 10.3). Rift models are discussed in Dunster and McConachie (in press)* and are no longer considered appropriate for the McNamara group as a whole. Southgate *et al.* (1996) suggested that the Paradise Creek Formation was deposited on an unrimmed shelf. Harris (1984; written comm. 1994), working to the northwest of the Lady Loretta mine, advocated a rimmed shelf with the high-relief microbialites in the Esperanza Formation forming a barrier on a gently dipping ramp. He believed that this barrier was contemporaneous with, and responsible for, the development of the highly pyritic and carbonaceous facies in the Lady Loretta Formation. In seeming contradiction, Harris (1984) also subscribed to the idea of a large syn-sedimentary graben at this time. Sami *et al.* (1997) suggested that the Esperanza Formation was deposited on a ramp that deepened to the south, with some build-up of microbialites to form a rim. In work that pre-dated the detailed studies of the Esperanza Formation, Dunster and McConachie (in press)* suggested that the Esperanza and Lady Loretta Formations were deposited on a broad carbonate platform and refuted previous interpretations of syn-sedimentary graben controls on sedimentation.

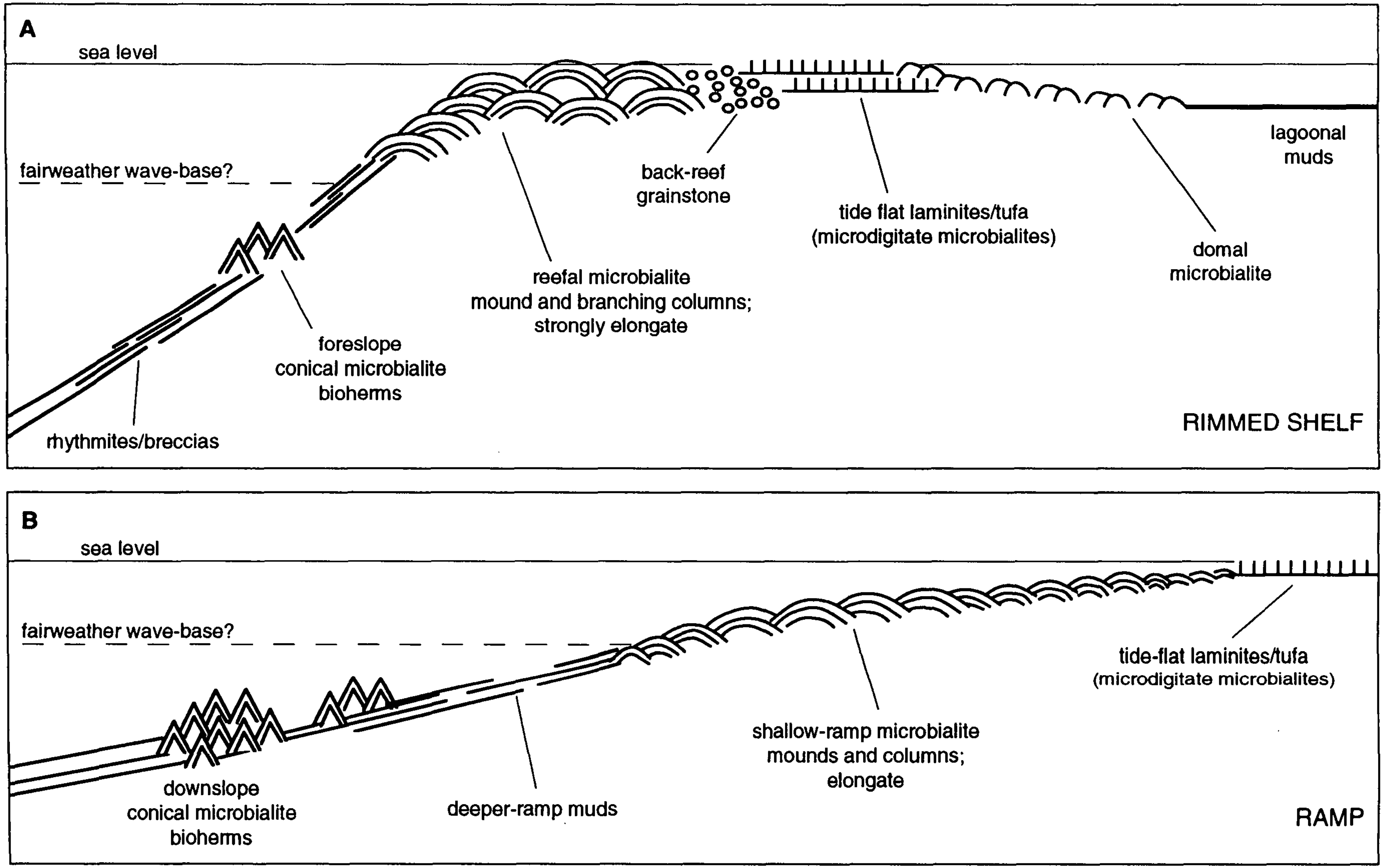
10.5 DEPOSITIONAL MODELS

10.5.1 Regional Depositional Model

The overall model proposed for the Lady Loretta Formation in this thesis is that of a ramp that dipped gently to the southwest. Well-developed carbonates and mixed carbonate/ siliciclastics were deposited in the northwest and argillaceous lithologies were deposited in the southeast. Reefal facies in Lady Loretta time would have constituted a localised rim behind which laterally extensive carbonate lagoons developed. This barrier probably existed for only a small proportion of the time of the deposition of the Lady Loretta Formation and was not as significant a feature as had been the case during the deposition of the Esperanza Formation. Argillaceous, carbonaceous and pyritic sediments were deposited in small isolated lagoons developed on the tidal flat during lowstands.

The author concurs with the palaeogeographic interpretation presented by Hutton and Sweet (1982) who proposed that a mountain range was present a few tens of kilometres to the west of the present orebody in what is now the Undilla Basin. This interpretation is based on the distribution and thickness of the Shady Bore Quartzite (Hutton and Sweet, 1982), palaeocurrent data from the Lady Loretta Formation, the distribution of highly micaceous facies in the Lady Loretta Formation and the distribution of arenaceous facies in the Esperanza Formation. A substantial thickness of redbeds and evaporite pseudomorphs occur in the Trent section between the mountains and the area of the mine.

Figure 10-3: The archetypical Proterozoic carbonate ramp proposed by Grotzinger (1989).


A
sea level
fairweather wave-base?
back-reef
grainstone
tide flat laminites/tufa
(microdigitate microbialites)
lagoonal
muds
domal
microbialite
reefal microbialite
mound and branching columns;
strongly elongate
foreslope
conical microbialite
bioherms
rhythmites/breccias
RIMMED SHELF
B
sea level
fairweather wave-base?
tide-flat laminites/tufa
(microdigitate microbialites)
shallow-ramp microbialite
mounds and columns;
elongate
downslope
conical microbialite
bioherms
deeper-ramp muds
RAMP

The Murphy Inlier was probably a significant palaeo-high to the distant northwest, but there is no evidence that Kamarga or Fiery Creek Domes were exposed as palaeo-highs at Lady Loretta time.

This regional depositional model proposed for the Lady Loretta Formation has similarities with those published by Bertrand-Sarfati and Moussine-Pouchkine (1983), and Handford (1986) for other carbonate and mixed carbonate/siliciclastic sequences that contain microbialites, evaporites and tempestites. It is also consistent with the archetypical model of Grotzinger (1989) and the work of Sami *et al.*, (1997) and Sami and James (1993, 1994). It represents a fundament shift from previous models for the Lady Loretta Formation that invoked a rift setting (see Dunster and McConachie, in press)*.

10.5.2 Depositional Model in the Vicinity of the Lady Loretta Ore Body

On the basis of the palinspastic reconstructions presented in Figure 10-4, the detailed core logs and measured sections in Appendix A-15 and the sequence stratigraphic correlation in Section 10.4, it is possible to propose a palaeogeographic depositional model for the vicinity of the Lady Loretta mine. This is shown, with artist's licence, in Figures 10-5 to 7. It is emphasised that this depositional model is supported by the interpretation of the facies that underlie, overlie and are laterally equivalent to the stratigraphy in the vicinity of the mine. Such an approach demonstrates that the Ore Sequence is enveloped by relatively shallow marine to tidal and emergent facies. The model proposed here precludes a subwave base deep water condensed sequence corresponding to a widespread MFS, as advocated generally for the SSHBM hosts in the Mount Isa Basin by Bradshaw *et al.* (1996b).

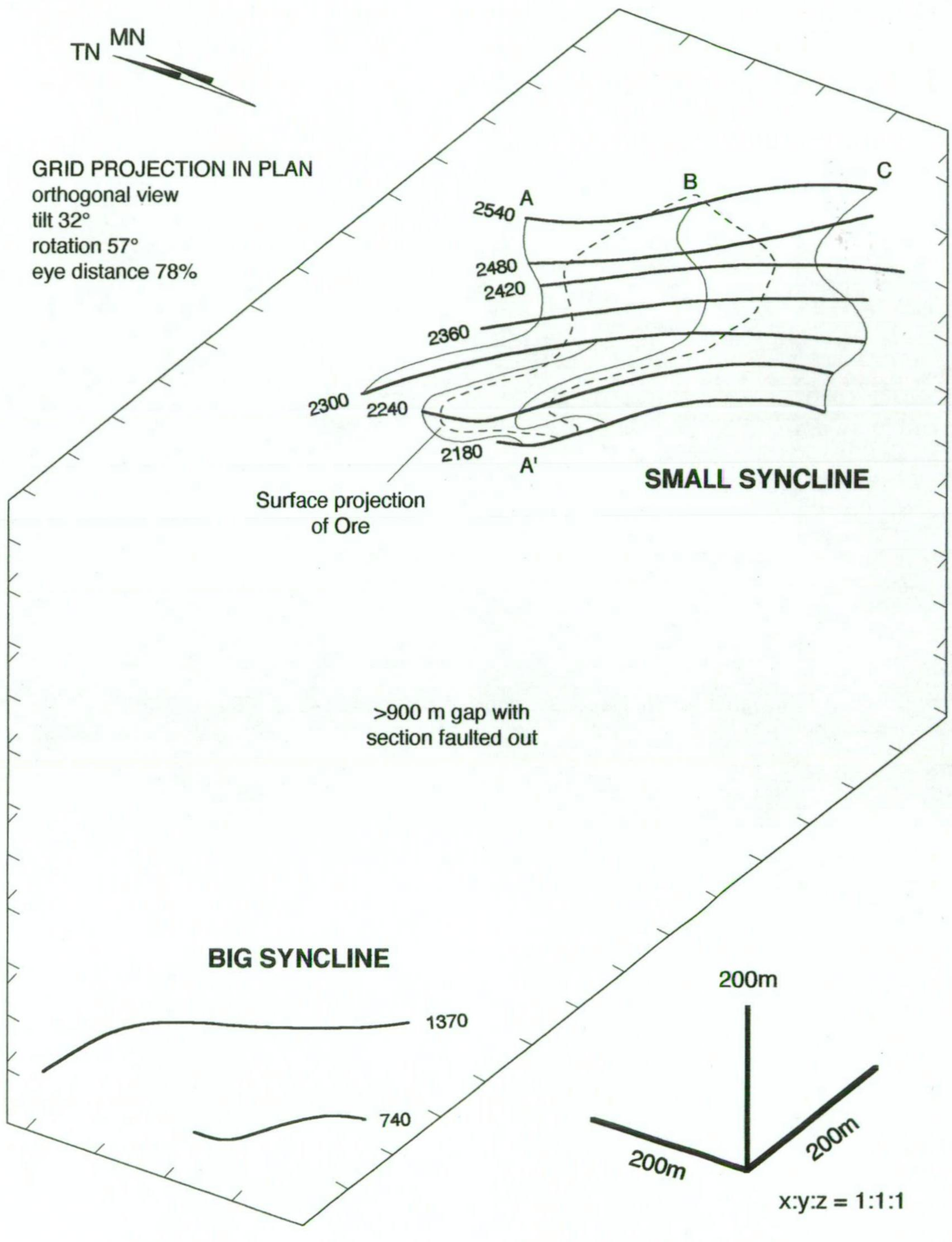
Figure 10-5 shows the environments of deposition proposed for the upper-most Esperanza Formation in the vicinity of the mine. High-relief vertical microbialites grew in deeper water offshore and low-relief bioherms and biostromes of elongate and inclined microbialites were common in the zone subject to wave and tidal action. A mountain range was present to the west.

Figure 10-6 illustrates the environments of deposition interpreted for the time of deposition of the host sediments at the Lady Loretta mine. The highly carbonaceous and pyritic shales and dolomitic siltstones were deposited subaqueously in a lagoon complex developed on a tidal flat. A red-bed sabkha was present landward of the lagoon.

By the time of the deposition of the units overlying the XXII horizon, the area was characterised by widespread shallow marine deposition (Figure-10-7).

Figure 10-4a: Key to following figures that are a series of vertical sections through both synclines, stepping progressively to the southwest, and showing a palinspastic reconstruction of the mine stratigraphy. The top of the Ore Sequence or Ore Sequence Equivalent is used as datum and the sections have no vertical exaggeration.

a



- Upper Clastic Unit
- Cyclic Unit
- Ore (12% Zn eq. cut-off)
- Ore sediments/Ore Sequence Eq.
- Cored intercept at top Ore Sequence
- Bedded barite
- Non-prone microbialites
- ?Gypsum moulds/pseudomorphs
- Pyritic Unit
- Cored intercept projected to line of section

Figure 10-4b: Reconstruction of sections 2540, 2480 and 2420.

b

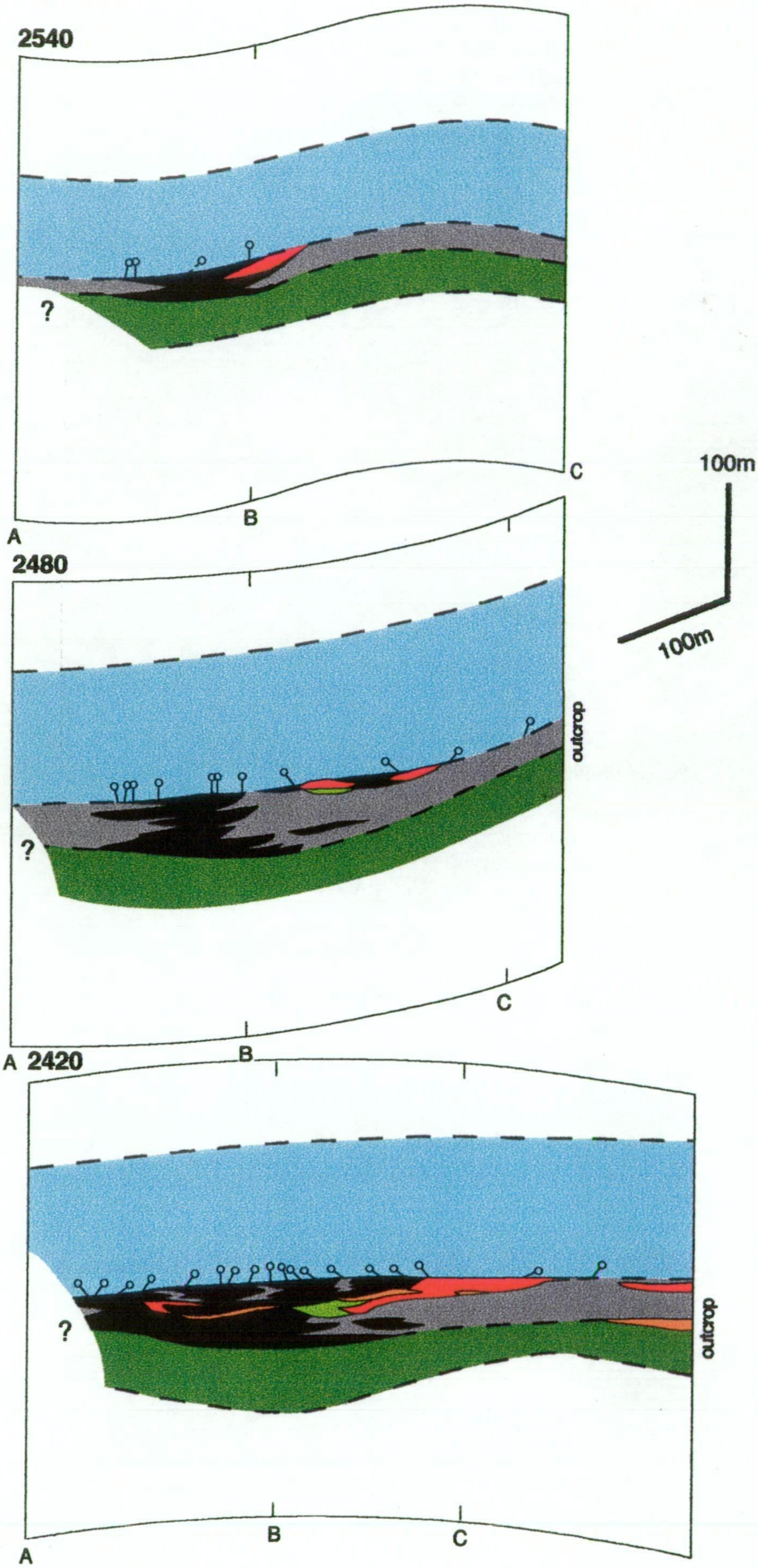


Figure 10-4c: Reconstruction of sections 2360, 2300 and 2240.

c

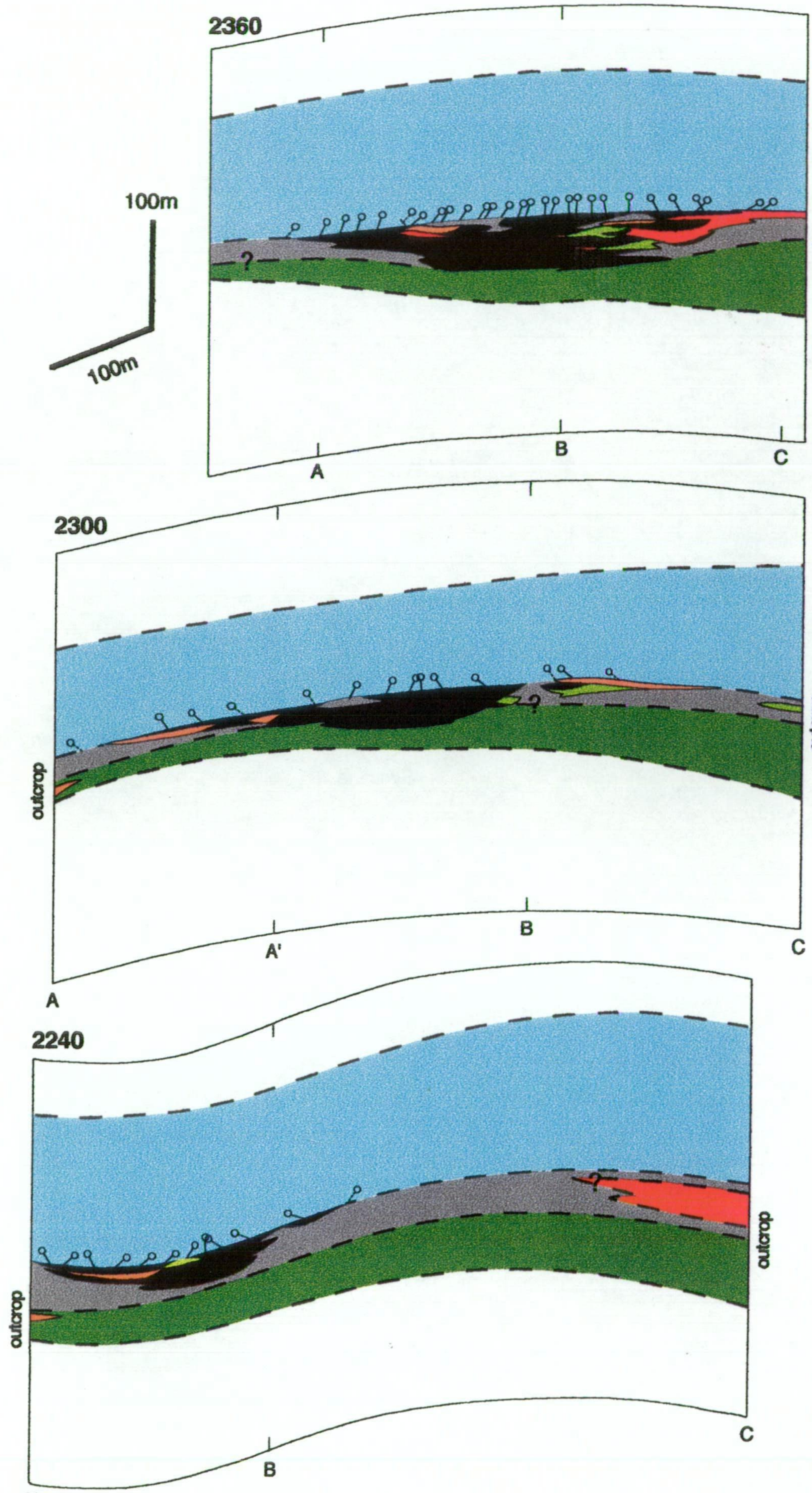

2360
100m
100m
outcrop
A
B
C
2300
outcrop
outcrop
A
A'
B
C
2240
outcrop
outcrop
A'
B
C

Figure 10-4d: Reconstruction of sections 2180, 1370 and 740. The last two are in the Big Syncline.

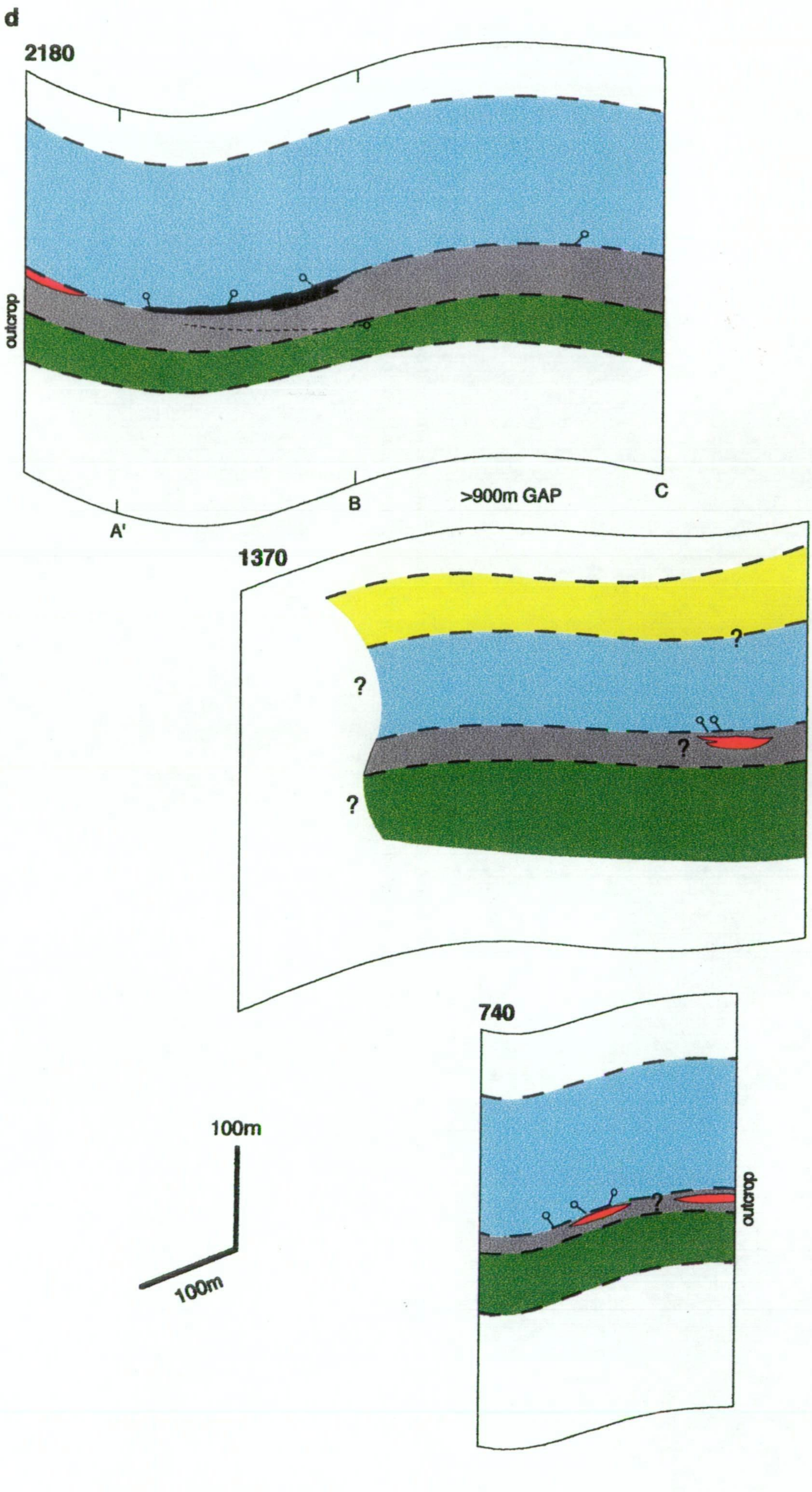
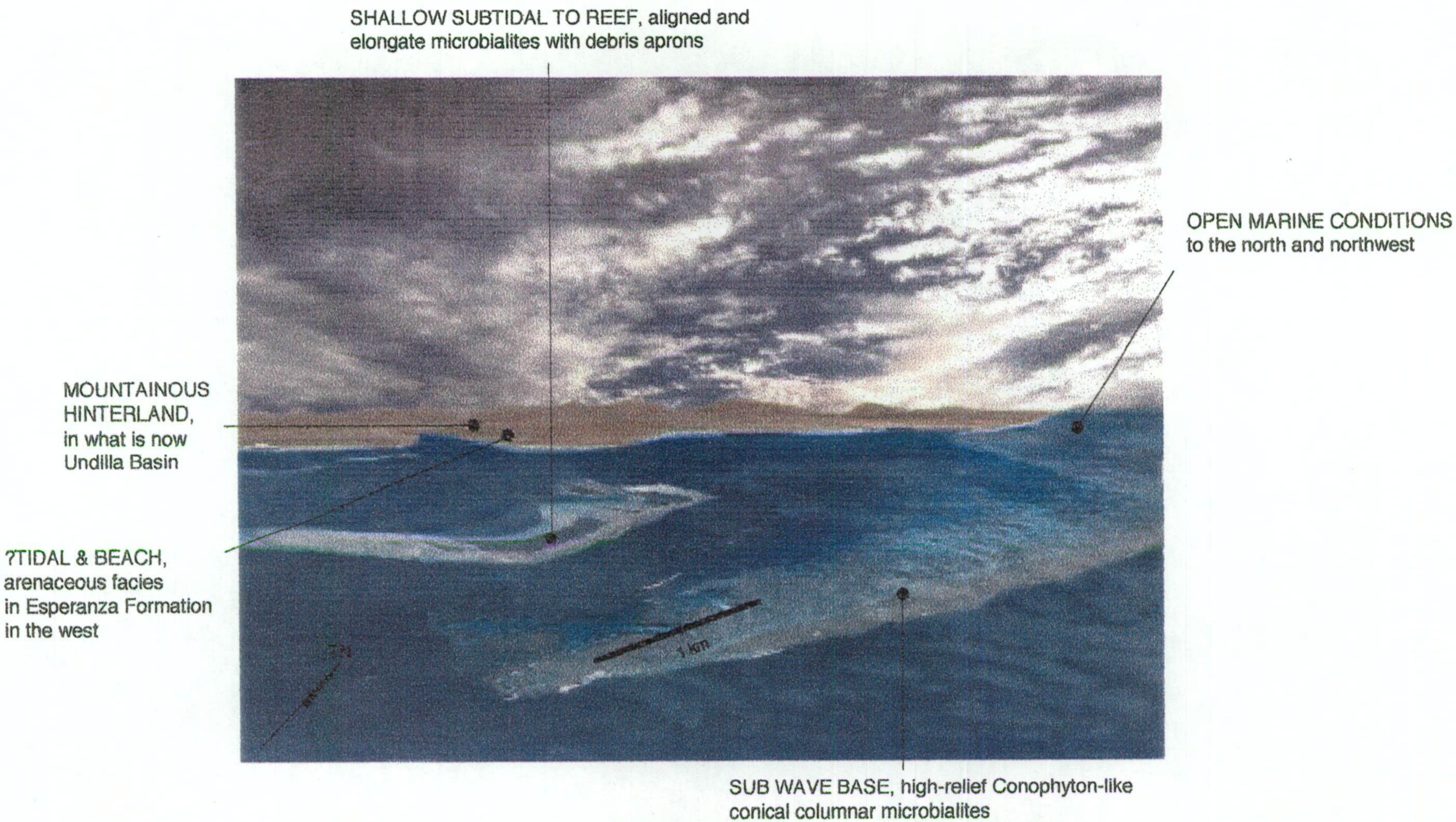

d
2180
outcrop
A'
B
>900m GAP
C
1370
?
?
?
?
outcrop
740
?
outcrop
100m
100m

Figure 10-5: A reconstruction of the depositional environments in the vicinity of the present Lady Loretta mine at a time just before stratigraphic horizon I, showing the abundant high-relief microbialites in the Esperanza Formation forming a barrier complex.



SHALLOW SUBTIDAL TO REEF, aligned and elongate microbialites with debris aprons
OPEN MARINE CONDITIONS to the north and northwest
MOUNTAINOUS HINTERLAND, in what is now Undilla Basin
?TIDAL & BEACH, arenaceous facies in Esperanza Formation in the west
1 km
SUB WAVE BASE, high-relief Conophyton-like conical columnar microbialites

Figure 10-6: A reconstruction of the depositional environments in the vicinity of the present Lady Loretta mine at a time corresponding to the XI-XII stratigraphic interval and showing deposition of the ore-host rocks in a lagoon.

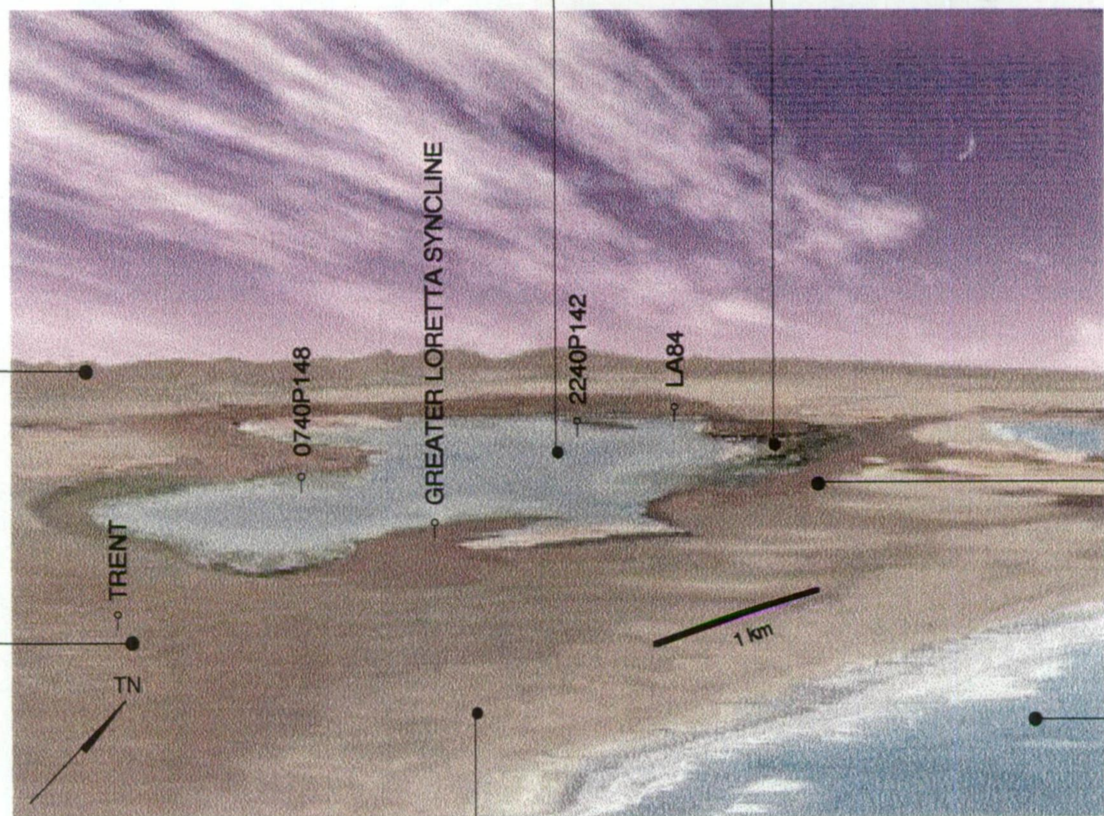
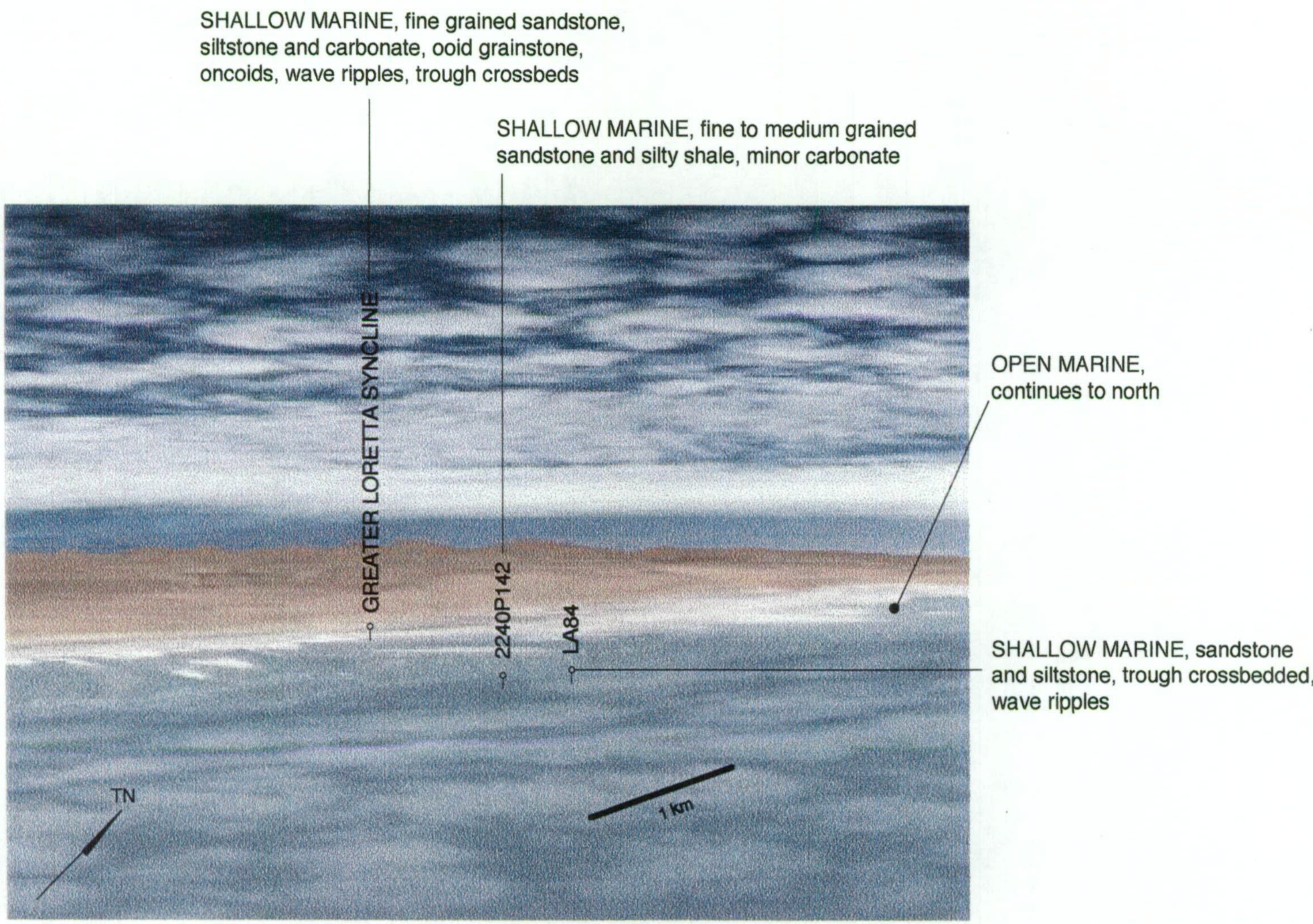

LAGOON, shallow subaqueous deposition of highly carbonaceous and pyritic argillaceous sediments and silty carbonates
MICROBIALITES, including domal and minidigitate forms on edge of lagoon, prolific prone microbial mat
?BARITE, concentrated on periphery of lagoon, thickest on eastern and western sides
MOUNTAINS, >10 km distant in what is now Undilla Basin
0740P148
GREATER LORETTA SYNCLINE
2240P142
LA84
TRENT
LAGOONAL MUDFLAT, laminated argillites and siltstone, euhedral displacive gypsum, desiccation cracks, synaeresis cracks
?SABKHA, red-bed siltstone, displacive sulphate evaporites, minor halite
1 km
TN
SHALLOW TIDAL MARINE, sandstone and siltstone, lenticular bedding, wave ripples, trough crossbedding
TIDAL FLAT, sandstone and siltstone, minor carbonate, flaser and lenticular bedding, wave and interference ripples

Figure 10-7: A reconstruction of the deposition at a time just after the XXII stratigraphic horizon, showing marine deposition in the environments in the vicinity of the present Lady Loretta mine.


SHALLOW MARINE, fine grained sandstone, siltstone and carbonate, ooid grainstone, oncoids, wave ripples, trough crossbeds
SHALLOW MARINE, fine to medium grained sandstone and silty shale, minor carbonate
GREATER LORETTA SYNCLINE
2240P142
LA84
OPEN MARINE, continues to north
SHALLOW MARINE, sandstone and siltstone, trough crossbedded, wave ripples
TN
1 Km

Chapter 11 - Diagenesis and Metamorphism

11. DIAGENESIS AND METAMORPHISM OF THE LADY LORETTA FORMATION

11.1 INTRODUCTION

This chapter presents a brief overview of the diagenesis and metamorphism of the Lady Loretta Formation. Several of the topics presented warrant studies in their own right, however the following discussion focuses on issues that are controversial and/or relevant to mineralisation.

11.2 DIAGENESIS OF ORGANIC MATTER

11.2.1 Organic Diagenesis and Possible Involvement in the Mineralisation Process

The roles of organic matter in normal sedimentary diagenesis (*e.g.* production of organic acids, hydrocarbon generation *etc.*) are well documented (see review in Gautier, 1986). The presence of organic-rich shales in the host rocks of SSHBM ore bodies is commonly used to argue for anoxic reducing, and therefore deep-water, deposition (see discussion in Demaison and Moore, 1980). The types of organic-derived material in SSHBM ore bodies can be interpreted to indicate a complex diagenesis involving bacterial, thermogenic and radiogenic maturation; generation and expulsion and possible subsequent re-mobilisation of different phases of hydrocarbons (see Section 4.8). However, the active involvement of organic processes and products in base metal mineralisation is commonly overlooked.

The proposition that large volumes of organic matter in a sediment can be uniquely interpreted to indicate deep-water anoxia is incorrect (Demaison and Moore, 1980). Highly organic shales are deposited in a variety of shallow water environments including peat and mangrove swamps, salt and fresh water lakes and lagoons. The volume of organic matter in a sediment is a function of both production and preservation (Wignall, 1994). Environments in which both of these factors are favourable will produce thick sequences of highly organic shale regardless of the water depth or the oxidisation state. This is because organic-rich sediment is readily compacted, and almost all sediment becomes anoxic in the very shallow subsurface.

As discussed in Section 13.5, one of the current models for the formation of the Lady Loretta ore body invokes early mineralisation in an environment characterised by a high degree of microbial productivity and large amounts of preserved organic matter. At such shallow burial conditions, organic diagenesis must have been contemporaneous with mineralisation. Although complex and difficult to model chemically, biological processes and the degradation of organic matter may have been involved in the mineralisation process.

Even in the case of late epigenetic models that invoke mineralisation by replacement of consolidated rock, the processes involved could be influenced by hydrocarbon maturation and migration. The presence of hydrocarbons is pivotal to the Broadbent *et al.* (1996) model for Century in which the underlying premise is that, in this case, a SSHBM ore body is a mineralised petroleum source/reservoir.

During the burial and diagenesis of organic matter, metals could preferentially partition into:

- a mobile organic phase with abundant hydrocarbons
- a non-mobile refractory organic phase
- an inorganic solid phase
- an aqueous phase (Johns and Shimoyama, 1972).

The combination of organic matter and metals occurs in several stages, as described below. At low, near-surface temperatures bacteria metabolise organic acids. Under such conditions with Ro (vitrinite reflectance) <1.2%, the major processes are the complexing and adsorption of metallic elements by enzymes in living organisms and by organic acids from dead organisms. Organic ligands are capable of transporting metals. As temperatures rise above 80°C, organic acids are produced from the thermal degradation of organic matter. Such acids can create secondary porosity in carbonates. Although early secondary porosity is not an obvious feature associated with SSHBM mineralisation, it may be implicated in MVT and Irish-type ore bodies.

Dissolved organic complexes are effective transport agents of metals. Organic acid anions are important in controlling the concentrations of metals because they affect the pH and buffer capacity of the waters at subsurface conditions. At about 120°C, organic acids begin to decompose to carbon dioxide and methane. Since this decomposition is a more gradual process, organic acids can still act as pH buffers even at elevated temperatures (Spirakis and Heyl, 1993).

Mineralisation models for ore deposits other than SSHBM ore bodies, both syn- and epigenetic, have appealed to organic reductants to localise precipitation from a metal-bearing brine. Spirakis and Heyl (1993) proposed such a model for MVT ore bodies; suggesting that the organic matter formed a substrate for bacterial metabolism, provided the organic acids that acted as reductants and liberated CO_2 from carbonates. Coincidentally, it is also conceivable that some of the barite in MVT ore bodies is a low temperature precipitate resulting from the bacterial breakdown of thiosulphate from the brine in the presence of organic matter (Spirakis and Heyl, 1993; see Section 13.4.9). Similar mechanisms can be invoked at the Lady Loretta ore body.

In summary, organic matter must play a much more significant role in the mineralisation process than merely acting as a reductant. All genetic models, whether they propose mineralisation at the sediment water interface, in unconsolidated sediment or epigenetic void-fill or replacement of consolidated rock, must consider the complexities of simultaneous organic diagenesis and/or hydrocarbon generation and maturation.

11.2.2 Thermal Maturity at the Lady Loretta Mine

The thermal maturity of organic matter from the Lady Loretta Formation has previously been assessed from cores of the Ore Sequence (Carr, 1981) and from drillhole Amoco 83-5 (Dorrins *et al.*, 1983). Additional analyses of TOC were undertaken during this study. The method of analysis is described in Appendix A-6.2. Determinations of TOC and thermal maturity are complicated by two sources of bitumen as described below.

The maturity of organic matter from Amoco 83-5 was assessed by Dorrins *et al.* (1983) as "past peak oil generation" implying reflectances above 2.0% using their criteria.

At the mine, Carr (1981) reported bitumen with a maximum reflectance of between 5.5% and 6.5% and a birefringence of 0.8%. Rare flakes of graphite along vein carbonate boundaries have reflectances of up to 9.6%. These reflectances are well past peak oil and gas generation.

During this study, another suite of samples was collected for organic petrographic description using modern techniques and the terminology of Crick (1989 *et seq.*). Vertical profiles from drillcores of representative drillholes in both the Big and Small Synclines (0740P148 and 2240P142, respectively) were used to compare unmineralised and mineralised intersections in the hope of identifying palaeo-thermal anomalies associated with mineralisation or the passage of mineralising fluids. Unfortunately, the majority of samples from the mineralised intersection did not contain suitably preserved organic matter. Reflectance data from suitable samples are summarised below.

Sample	n	OM type	Rand. Ro%	95% Confidence		Min	Max	Max Ro%
				lower	upper			
2240P142, 158.9	21	mb	5.20	4.95	5.45	4.20	6.20	8.00
2240P142, 224.0	9	mb, pb, db	4.96	4.64	5.27	4.40	5.60	7.60
2240P142, 330.0	9	mb	5.53	5.15	5.92	4.80	6.40	8.56
0740P148, 108.55	12	pdb, mb, nf lam	4.44	4.25	4.64	3.80	4.80	6.72
0740P148, 157.0	17	mb	5.73	5.48	5.98	5.00	6.60	8.89
0740P148, 199.0	22	mb	4.47	4.31	4.63	3.60	5.20	6.77
0740P148, 207.0	14	mb	4.43	4.23	4.63	4.00	5.20	6.71
0740P148, 212.0	16	mb	5.05	4.85	5.25	4.40	5.60	7.75
0740P148, 244.0	20	mb	5.01	4.82	5.20	4.20	5.60	7.68
0740P148, 262.0	20	mb	5.37	5.18	5.56	4.60	6.00	8.29

Table 11-1: Reflectance values and statistics for organic matter in the vicinity of the Lady Loretta mine from Crick (1997). Abbreviations: Sample - cored drillhole and driller's depth in metres, n - number of measurements, OM type - type of organic matter, pdb - patches of dispersed bitumen, mb - matrix bitumen, nf lam - nonfluorescing lamalginite (presumed, not defined in Crick, 1997), Rand. Ro% - mean random reflectance, min - minimum value, max - maximum value, max Ro% - maximum reflectance.

Several important points regarding the thermal maturity were noted by Crick (1997) and are discussed below.

All the reflectances are above the oil window that lies between 0.2-1.5 max Ro% using the criteria of Crick (1997). Many of the samples (*e.g.* 0740P148, 199 m - Figure 11-1) have a distinctly bimodal distribution of reflectances. These populations of higher reflectances were interpreted as thucholitic bitumen developed around radioactive grains (see Section 4.8) and these data were not included when assessing the thermal maturity.

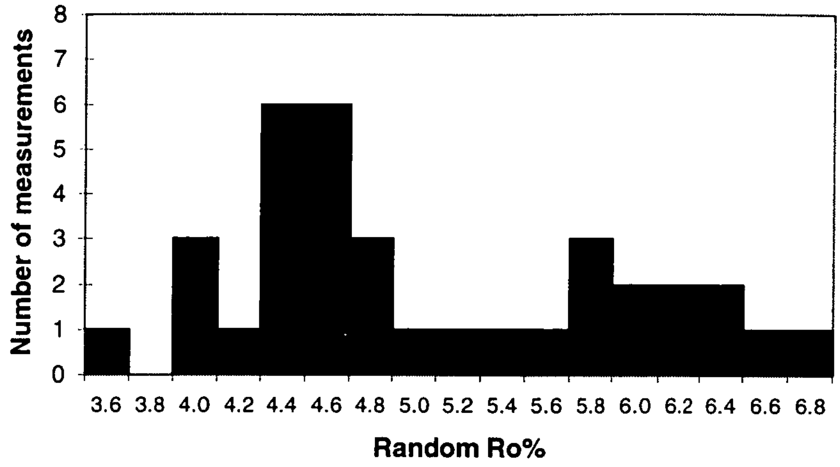
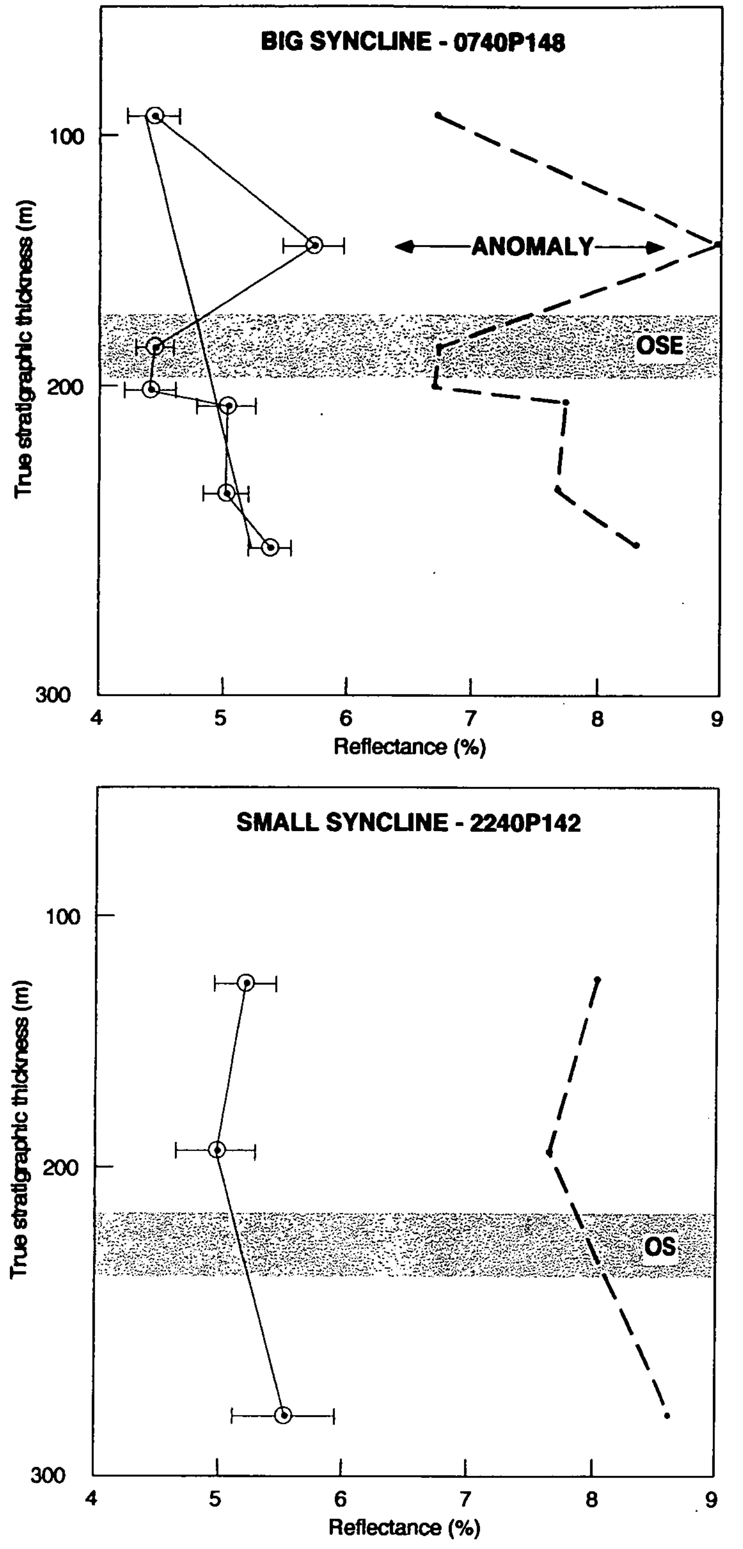


Figure 11-1: Random reflectance versus number of measurements from drillhole 0740P148, 199 m. Modified from Crick (1977).

Figure 11-2 shows the downhole reflectance profiles corrected to true stratigraphic thickness and relative to the level of mineralisation. Whereas the reflectance profiles from most drillholes show a regular increase in thermal maturity with depth, 0740P148 contains anomalously high thermal maturity at 157 m (driller's depth). An anomaly of this magnitude cannot be a statistical aberration, nor can be explained by faults in the section or the mis-labelling of core depths. It is interpreted to reflect unusual intraformational heating. As there are no igneous intrusions present, the passage of a hot fluid seems the most likely explanation. It is noteworthy that this is 12 m stratigraphically *above* the Ore Sequence Equivalent in the unmineralised Big Syncline. As such, it may support the late epigenetic base-seal mineralisation model advocated by McConachie and Dunster (1996;* see Section 13.5). It is also significant that there is no discernible palaeo-thermal anomaly associated with the oxidised zone immediately below the Ore Sequence Equivalent, that could be interpreted as a conduit.

Although there are few data from the mineralised intersection (2240P142), there does not appear to be a palaeo-thermal anomaly in the Small Syncline in the same stratigraphic position relative to the Ore Sequence.

Figure 11-2: Comparison of downhole reflectance profiles for drillholes 0740P148 and 2240P142.



⊙ Random Ro   ├─┤ 95% confidence limits   ╲ Maximum Ro

OS Ore Sequence Equivalent   **OSE** Ore Sequence

11.3 CARBONATE DIAGENESIS - THE ORIGIN OF SIDERITE

The carbonates of the Lady Loretta Formation have undergone a complex meteoric and deep burial diagenesis, including what is interpreted as pervasive early dolomitisation. A comprehensive documentation would constitute a study in its own right. Appendix A-8 describes some of the alteration inferred from the major and trace element chemistry and relates this to exploration geochemistry.

Physical structures such as stylolites and dissolution seams (Railsback, 1993) have been documented from the ore host rocks by Carr (1983) and are locally common in outcrop in a variety of carbonate lithologies throughout the formation. Such features are testament to considerable pressure solution.

The following discussion focuses on the formation of siderite in the Lady Loretta Formation since this has implications for potential genetic models of mineralisation and remains a contentious issue.

11.3.1 Formation and Significance of Siderite

Before this study, many workers had considered the siderite at the Lady Loretta mine to be a primary carbonate unique to the mine stratigraphy. Its presence was cited as evidence of a highly reducing anoxic (and therefore deep water) depositional environment. Several authors advocated a SEDEX origin or interpreted it as, at least, indicative of hydrothermal activity (*e.g.* Lemcke, 1986). In these cases, the siderite was supposed to have formed from the same fluids that carried the metals. The following discussion disputes these origins, at least in the case of Lady Loretta.

Siderite is relatively common in the geological record. It occurs in rocks from a wide variety of different depositional and diagenetic settings including marine and non-marine oil shales and coal. One feature in common is the abundance of Fe and carbonaceous matter in the associated rocks. Siderite formation in coal commonly involves displacive growth in uncompacted sediment followed by one or more early epigenetic generations of differing chemical composition (Patterson *et al.*, 1994).

Siderite is abundant in the Century SSHBM ore body and is also present at Mount Novit, Hilton, and George Fisher mines (Mount Isa). It is believed to be absent at HYC, although other Fe-carbonates are present. The siderite at Century is much more coarsely crystalline than that associated with the Lady Loretta ore body and may not have originated in the same way.

Siderite at the Lady Loretta mine is not exclusive to the alteration envelope around the ore. Siderite veins occur in what is probably Esperanza Formation, below the Carlton Fault Zone and *ca.* 80 m below the ore and are also present in stratigraphically lower rocks that host copper mineralisation north of the Carlton Fault Zone. Sideritic alteration and siderite veins extend several kilometres from the mine; at least as far as drillholes LA64 and LA65 in the Tom Cat area. In core from LA64, sideritic alteration and siderite veins are present *ca.* 200 m above the Ore Sequence Equivalent.

As documented in Appendix A-8, Fe-rich carbonates, including sideritic alteration of bedded carbonates and siderite veins, occur in carbonaceous and pyritic rocks from several stratigraphic levels in the Lady Loretta Formation including the Carrier and Johnson Creek areas.

Obviously, siderite is not restricted to the vicinity of the ore body and cannot be considered indicative of any particular depositional or diagenetic environment. It is certainly not exclusive evidence of sea-floor exhalation.

The first detailed study of the origin and timing of the siderite at the Lady Loretta mine was by Carr (1981), who identified two generations. The first generation is inclusion rich and the later generation consists of recrystallised ground mass, veins and vugs. Carr (1981) demonstrated that there was a similar wide variation in the chemical composition of both generations of siderite with the exception of Zn. The first generation siderite is generally, but not consistently, higher in Zn than the later generation.

Pertinent textural observations by Aheimer (1994) and the author have demonstrated that these first generation Fe-rich carbonates are most common adjacent to, especially above, the contact between carbonaceous pyritic interbeds and altered silty dolostone. In core that has been exposed to the atmosphere, this is manifest as brown alteration that extends for up to several centimetres away from the source of the Fe (see Plate 4.5 in Aheimer, 1994). A similar relationship results in the formation of a sideritic halo around isolated pods of pyrite in silty carbonate rock. Conversely, carbonate idens tectonically emplaced in high-Fe lithologies have a rim of sideritic alteration. Siderite is also common adjacent to the carbonaceous and pyritic matter concentrated in regions of pressure solution. All these zones of alteration consistently stain for siderite, but microprobe studies of a bedded example showed an intimate mixture of various Fe-carbonates ranging from impure ferroan dolomite, through ankerite to almost pure siderite (Duhig, 1994).

These textures and chemistry are consistent with the formation of first generation siderite by diagenetic alteration of pre-existing dolomite with the Fe being sourced from the adjacent pyrite. This is also consistent with the geochemical modeling by Cooke *et al.* (1994) who considered that the siderite may be "a low temperature, late diagenetic overprint on sulphide mineralisation, with abundant pre-existing iron sulphides providing a local source of Fe that helped stabilise siderite over dolomite" (Cooke *et al.*, 1994). This interpretation may not explain the siderite at Century where there is relatively little pyrite.

Whereas the origin is now reasonably well constrained at Lady Loretta, the timing of siderite formation is not. Textural observations of cores from the mine indicate that some first generation siderite pre-dates mircofracturing but alteration of tectonically emplaced idens suggests that "first generation" sideritic alteration continued after the formation of the synclines and may have been synchronous with, or even post-date "second generation" vein siderite. Stylolites both cross-cut and constrain bedded sideritic alteration. Siderite veins both crosscut and are cut by stylolites. Siderite veinlets cut feldspar-chert beds and are in turn cut by galena-filled fractures. In some mineralised tension gashes, siderite forms the outer rim and galena the central core. Collectively, such evidence can be used to argue for a relatively long-lived process of formation or, alternatively, several periods of diagenetic siderite formation in the mine sequence.

11.4 SILICA DIAGENESIS

11.4.1 Introduction

As described in Chapter 4, the Lady Loretta Formation has undergone a complex silica diagenesis that includes:

- pervasive regional incipient and locally intense silicification
- the formation of bedded chert in the vicinity of the ore body
- the so-called "silica-dolomite" that hosts minor Cu mineralisation at several locations
- the development of cauliflower cherts by the silicification of evaporites.

11.4.2 Regional Silicification

Several formations in the McNamara Group, including the Esperanza Formation and the Mount Oxide Chert member of the Paradise Creek Formation, are regionally silicified in outcrop. Although there is debate over whether the silicification persists at depth, much of the Lady Loretta Formation contains at least incipient silicification to depths of several hundred metres. There are few constraints on the timing of the regional silicification, other than that it postdates dolomitisation of the carbonates and, in part, at least, postdates the formation of some pressure solution features.

The carbonates in the Lady Loretta Formation at Kamarga Dome are preferentially silicified in zones of originally high porosity and permeability. This is especially obvious in ooid grainstones, plate breccias and high-relief microbial facies. Some authors (*e.g.* Harris, 1984) argued that such silicification must pre-date the occlusion of porosity and hence be either near-surface and/or relatively early in diagenesis. An analogy can be drawn with the direct inorganic silica precipitation in the Coorong Lagoon, where silica is dissolved from detrital quartz by alkaline lake waters and is re-precipitated when the pH drops as a result of interaction with organic acids associated with organic matter (Peterson and Von der Borch, 1965). High temperatures are not necessary, as opal-CT silica is thought to precipitate at near-zero temperatures in Antarctic deep-sea sediments (Botz and Bohrmann, 1991). However, there is no modern analogue of syngenetic silicification at a scale appropriate for the Proterozoic examples. An epigenetic model, based on theoretical modeling, invokes silicification to produce bedded cherts at temperatures of 35-50°C and indicates that it may occur as low as 17-21°C (Matheney and Knauth, 1993).

11.4.3 Bedded Chert at the Lady Loretta Mine

Bedded chert is most prominent in outcrop of the Ore Sequence Equivalent in both synclines, but decreases in abundance to the northwest in the Big Syncline. Some of this silicification is almost certainly a surface affect, since bedded chert is much less common in cored intersections. In hand specimen, the chert ranges from finely laminated grey to dark grey and to pale brown and massive. In thin section, the chert ranges from 2 to 10 μm and the laminae are defined by variable proportions of sericite, pyrite, barite and carbonaceous material. Dolomitic grains and diffuse patches of altered carbonate occur disseminated throughout the rock (Carr, 1981). Much of the bedded chert contains sedimentary and microbial features identical to the other host rocks. Aheimer (1994) and the author illustrated several examples where prone laminites are preserved in bedded chert (see Section 8.3). Low angle trough cross bedding, ripple crosslamination and gypsum pseudomorphs also occur.

A variation of the bedded chert in outcrop at the mine is locally referred to as "honeycomb chert". Previously thought to be unique to the mine, the present study also identified "honeycomb chert" in the Trent area. The characteristic texture is defined by scattered rhombohedral to irregular shaped voids up to 2 cm across. The voids are commonly concentrated along fractures and bedding planes. Neither the voids, nor their original contents, are present in cored intersections. Russell *et al.* (1976) and Carr (1981) correlated the honeycomb chert to the zone of most intense sideritic alteration in the subsurface. Russell *et al.* (1976) favoured pyrite as the original void-fill; whereas Carr (1981) suggested that it was coarsely crystalline siderite. Attempts to identify the original void-fill during this study were unsuccessful.

In support of a SEDEX model for the base metal mineralisation, the bedded chert at the mine had been assumed to be a high temperature hydrothermal deposit (*e.g.* Large, 1980, 1983). However, the textural evidence can be interpreted to indicate that the bedded chert formed by the silicification of sedimentary rocks identical to those in the surrounding package. The widespread silicification of microbialites in the underlying Esperanza Formation is further evidence that such cherts need not be hydrothermal in origin.

11.4.4 Silica-Flood and Silica Veining

Silica-flood, also locally referred to as "silica-dolomite" is the pervasive silicification of a dolomitic host that results in an intimate mixture of the two minerals with a crystal size that varies from aphanitic to coarsely grained. In fresh core, the white or pale red-brown colour is very distinctive; contrasting markedly with the host rocks. The silica-flood typically has a sharp but irregular boundary that may be stratigraphically concordant at a broad-scale but is clearly crosscutting and replacive in hand specimen. The best examples of silica-flood in the Lady Loretta Formation are in cores from drillholes about 80 m below the ore body, associated with the Carlton Fault Zone, and drillhole CM35 to the northeast of the mine. Both examples are associated with locally intense quartz veining and minor Cu mineralisation. In both cases, the silica-flood is post stylolitisation, but some silica-flood postdates earlier silica veins.

Quartz veins are present in outcrop adjacent to faults and in several cored intersections of the Lady Loretta Formation. They are relatively common in the vicinity of the mine. Aheimer (1994) distinguished between fibrous crack-seal veins and veins containing euhedral quartz crystals. On the basis of multiple generations of fluid inclusions, he suggested that the fibrous vein-quartz was early and that the euhedral form was later; possibly forming as a recrystallisation of fibrous veins. This is consistent with their crosscutting relationships.

11.4.5 Formation of Cauliflower Cherts

The cauliflower cherts of the Lady Loretta Formation are described in Section 9.3.2 and interpreted as replacement of sulphate evaporite nodules. They provide a means of documenting the complex silica diagenesis. Since the cauliflower cherts from Kamarga Dome contain visible Pb and Cu mineralisation, they can be used to establish the relative timing of a mineralisation event, at least locally. Smaller cauliflower cherts in core from Amoco 83-5 retain sulphates and also host pyrite.

The primary sulphates were probably gypsum and anhydrite. Textures diagnostic of the latter are pseudomorphed by the chert (see Section 9.3.2). A sulphate diagenesis involving alteration to barite and/or celestite is interpreted and is consistent with the relatively high Ba and Sr analyses obtained from cauliflower cherts in Amoco 83-5. Rarely, remnant anhydrite remains as isolated optically-continuous inclusions. Larger inclusions of barite and/or celestite within the chert can be interpreted to suggest alteration to these less-soluble sulphates prior to the majority of silicification.

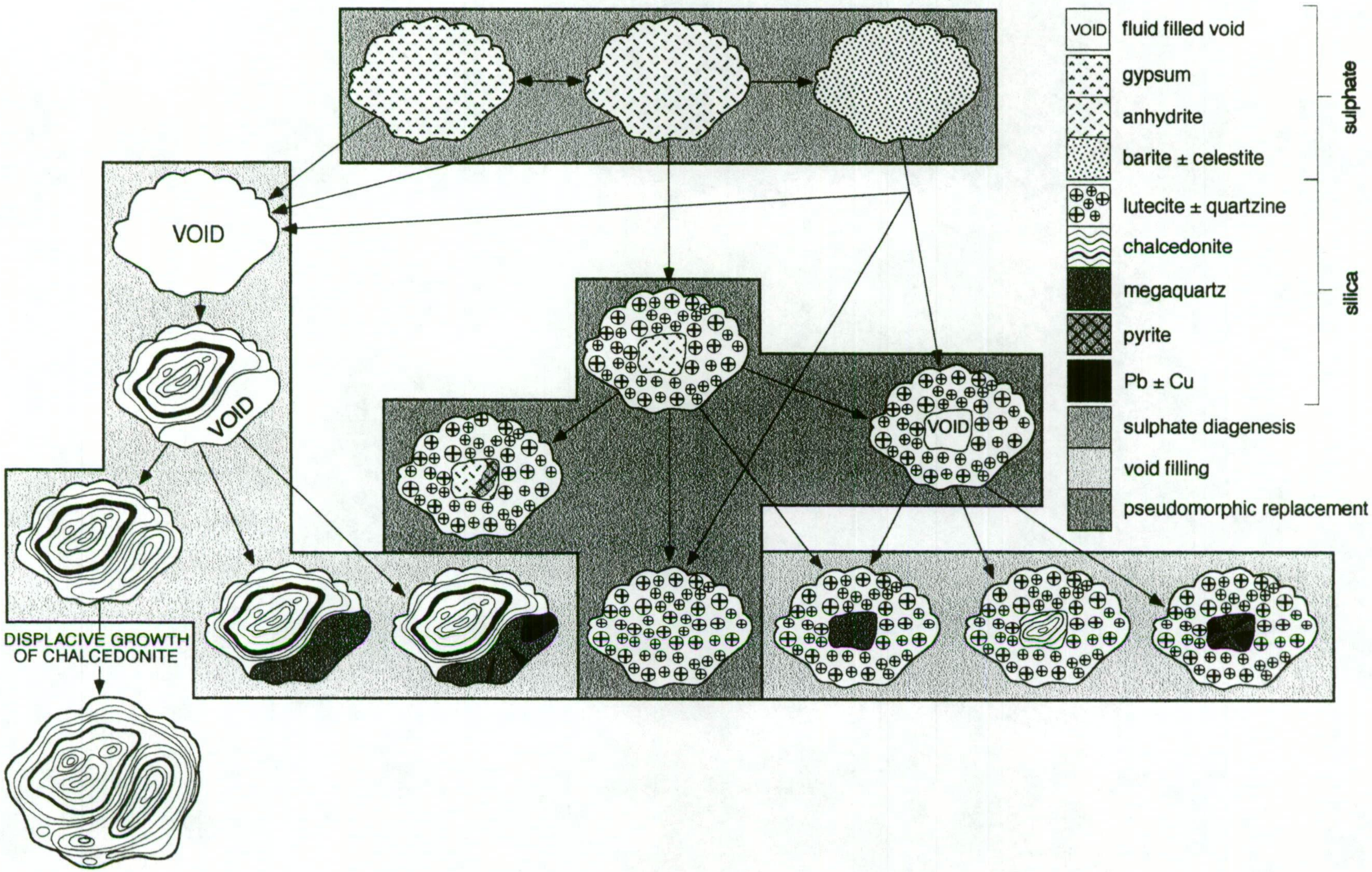
Two main processes appear to be involved in the formation of the cauliflower cherts (Figure 11-3). The sulphates may be pseudomorphed by lutecite and/or quartzine, or the sulphates can be dissolved to form a void that is then infilled by chalcedonite and/or megaquartz (the varieties of quartz are described in Section 4.6).

The silica that pseudomorphs sulphate is dominantly fibrous and pseudo-fibrous length-slow lutecite with subordinate quartzine. The lutecite commonly occurs as spherulites that have radial or fan-like undulosity. Length-slow quartz in cauliflower cherts has been considered diagnostic of former sulphate evaporites by several workers (*e.g.* Folk and Pittman, 1971) but it is also known to form in non-evaporitic settings. Heaney (1995) recognised that a variant of length-slow quartz called moganite was diagnostic of former evaporites, but it is metastable over geological time and not known to be preserved in rocks older than Cretaceous. Milliken (1979) found that first generation length-slow quartz in cauliflower cherts formed from fluids intermediate in composition between seawater and meteoric water and that replacement occurred at ambient surface temperatures. In the cauliflower cherts from the Amoco 83-5 core, pyrite forms within the sulphates but post-dates the earliest generations of lutecite.

The first generation of void-fill silica forms zebraic concretionary colloform rinds with characteristic brown and white banding in plane light. Where primary cavities still exist in the cauliflower cherts they are lined by either chalcedonite or coarse dog-tooth crystals of megaquartz. Milliken (1979) found that zebraic chalcedonic chert in cauliflower cherts was of meteoric composition, and formed at temperatures of less than 40°C.

Megaquartz most commonly occurs as a late-stage void-fill typically found in the centre of the nodule surrounded by lutecite. Rarely, the megaquartz and the contiguous lutecite are in optical continuity. Some megaquartz contains inclusions of sulphate and this

Figure 11-3: Formation of cauliflower cherts from original sulphate evaporite nodules by alteration, replacement, solution and void filling processes. Diagram based on Dunster (1987) and Radke (1982).



VOID
VOID
VOID
VOID
DISPLACIVE GROWTH OF CHALCEDONITE
fluid filled void
gypsum
anhydrite
barite ± celestite
lutecite ± quartzine
chalcedonite
megaquartz
pyrite
Pb ± Cu
sulphate diagenesis
void filling
pseudomorphic replacement
sulphate
silica

can be interpreted to suggest that it was also replacive. Lead and copper appear to be only associated with void-filling megaquartz and, as such, were introduced in the final phase of silica paragenesis.

Although the overall paragenesis of the cauliflower cherts presented here is similar to other examples described by Fairchild and Herrington (1989), Dunster (1987), Milliken (1979) and Radke (1982), it is significant that the examples from the Lady Loretta Formation contain no relict or secondary carbonates. This warrants further investigation, since it may indicate the pH of the various fluids involved.

11.4.6 Silicification of Ooid Grainstones

Silicified ooid grainstones have been a preferred object of petrographic studies of silicification, particularly in order to determine the relative timing of ooid and cement silicification and whether silicification has proceeded outward from the nucleus or inward from the rim (Hesse, 1990).

Examples of silicified grainstones in core of the Lady Loretta Formation demonstrate that such silicification is not a modern surface effect. Both ooids and cement are either wholly or partly pseudomorphed by various forms of quartz. Petrographic studies showed that ooid nuclei and/or one or more concentric zones in the cortex were preferentially silicified by microquartz (see Chapter 6). The silicification of the nuclei formed as either an overgrowth and/or by the recrystallisation of an original detrital quartz grain. The zones of preferential silicification within the cortex probably reflect areas of higher porosity and permeability associated with an original more-coarsely crystalline carbonate. Rarely, euhedral quartzine or lutecite forms non-preferential cross-cutting crystals. All these relationships can be demonstrated in a single thin section and can be interpreted to indicate no preferred path for silicification of the ooid grainstone (*cf.* Hesse, 1990). As no carbonate inclusions were detected in the late stage void-fill of megaquartz, it is possible that these are primary quartz cements and that silicification occurred before significant compaction. However, it is impossible distinguish texturally between the megaquartz from a wholly replaced or pseudomorphed coarse carbonate cement.

11.5 BEDDED GYPSUM AND SATIN-SPAR VEINS

Gypsum occurs within the vicinity of the Lady Loretta mine as bedding-parallel layers and, more commonly, as crosscutting veins. Both types are sporadically distributed throughout the mine stratigraphy and are most abundant in the Lower Carbonate Unit. Hancock and Purvis (1990) stated that gypsum was most common at the siderite-dolomite contact. Observations made during this study indicate that this may be the case in the Small Syncline, but does not appear to be true in the Big Syncline.

As described in Section 9.2.3, the gypsum beds (<5 cm thick) were described by Carr (1974, 1983) from core of the Lower Carbonate Unit at the Lady Loretta mine. Although this stratigraphic interval contains numerous gypsum veins, Carr (1974, 1981) recognised these beds as texturally distinct, however the original material is not available for further study. Little significance can be placed on the few $\delta^{34}S$ values (+7.8 to +15.1%) for bedded gypsum obtained by Carr (1981), although he concluded that, on this basis, a simple evaporitic origin was unlikely.

Three types of gypsum veins occur at the Lady Loretta mine. The most abundant are non-fibrous veins that range from millimetres to greater than 10 cm thick and contain numerous wall rock clasts. The second type are generally thinner and internally fibrous with one or more generations of inclusion-rich gypsum crystals aligned at right-angles to the vein wall. Wall rock clasts are less common in this type of vein. Very rare coarsely crystalline poly-mineralic veins have a core of gypsum followed by an enveloping layer of dolomite or layers of siderite and dolomite.

The fibrous veins can be interpreted as crack-seal features similar to satin spar gypsum veins described by Gustavson *et al.* (1994) and a similar origin can be inferred. Gustavson *et al.* (1994) found that, where pyrite is oxidising and anhydrite is hydrating to gypsum, the large volume of calcium sulphate released can be transported considerable distances in solution and be deposited as antitaxial gypsum veins in bedding-parallel extension fractures.

Crosscutting relationships and the tectonic folding of the fibrous veins can be interpreted to suggest that they formed earlier than the non-fibrous gypsum veins. The non-fibrous veins, including the poly-mineralic types, are interpreted to have been emplaced during the major folding event that formed the synclines. It is also significant that they contain only very minor visible mineralisation, possibly indicating that mineralisation pre-dated the formation of the non-fibrous gypsum veins.

11.6 ORIGIN AND DIAGENESIS OF FELDSPAR-CHERT ROCKS

11.6.1 Description

The Lady Loretta Formation contains numerous thin beds of distinctive pink to pale brown or pale green feldspar-chert rocks. They were first documented by Taylor (1973) who described authigenic feldspar beds in drillhole DDHJ1 at Johnson Creek. Hutton and Wilson (1984) described pink-orange and green beds comprised of aphanitic microcline, sanadine and quartz from outcrop near the Seymour River and Berg (1986) described similar beds from drillcore in the Carrier area. Feldspar-cherts also occur in other formations in the McNamara Group and in the Mount Isa Group and the McArthur Basin.

In the vicinity of the Lady Loretta mine, >25 such beds ranging up to 15 cm thick, occur throughout the stratigraphy from the Lower Carbonate Unit to the Cyclic Unit, corresponding to *ca.* 150 m below ore to *ca.* 80 m above ore (Carr, 1981). A pink to pale brown variety from the Lady Loretta mine was described by Carr (1981) as thin bedded aphanitic to finely crystalline beds made up essentially of fine grained anhedral K feldspar (average of 94.2 wt% orthoclase in 12 samples) with rare angular quartz crystals, apatite, zircon, muscovite and carbonate. Wisps of organic matter, sub-millimetre euhedral diagenetic pyrite and trace sphalerite also occur. Samples containing pyrite were examined in thin section in the hope of finding relict textures within the pyrite, but this proved

Figure 11-4: Feldspar-cherts from the vicinity of Lady Loretta mine. (a) "Carr's Tuff" from outcrop in the Big Syncline, sample LLD207. All the available material contains quartz veins. (b) Feldspar-chert from 429 m in the shaft, LLD5. (c) Feldspar-chert collected from the ore stockpile. Specimen 109988 in the University of Tasmania collection. Specimen is unoriented. (d) Feldspar-chert in core from drillhole 2280ED75, 89.5 m. These beds cannot be correlated to adjacent drillcores despite good drilling control. (e) A specimen from core demonstrating that the alteration responsible for the characteristic colour does not extend into the same bed on the other side of the fracture shown by the arrow. Also note the rounded ?clasts of K feldspar groundmass visible on the right, 2270WD05, 65.5 m. This specimen was also illustrated in Aheimer (1994). (f) Distinctive green feldspar-chert bed (above the geology pick) in the L3C costean. Bar scale is 1 cm.


a
b
c
d
e
f

unsuccessful. Some of the beds contain rounded aggregates of the K feldspar groundmass (Figure 11-4e). The SiO_2 contents of the pink feldspar-cherts varies between 60 wt% and 70 wt% (Carr, 1981). Carr (1981) described the beds as having sharp bases and diffuse tops, but as shown in Figure 11-4, this is not visible in all examples. This grading is better expressed in the K feldspar content, which is consistently marked by a sharp increase at the base of the bed and a gradual decrease at the top. Trace amounts of K feldspar persist for up to 1.5 cm above the limit of the pink colouration (Carr, 1974; pers. observation). The internal texture of the beds is aphanitic and glassy. Fresh samples have a conchoidal fracture, resembling chert. Typically, the beds are internally fractured or veined, commonly at a high angle to bedding. Where the pink beds occur adjacent to highly carbonaceous beds, the contact is commonly marked by haematite (visible in Figure 11-4b and c). Russell *et al.* (1976) suggested that these zones were also anomalous in Hg. Attempts to use the visible colouration for correlation in cores of the Ore Sequence have been unsuccessful and the beds cannot be traced laterally any more than a few hundred metres in outcrop. Similarly, whereas the beds are conspicuous on total-count gamma logs because of the relatively high K content, attempts to use the high gamma response to correlate the beds were unsuccessful (based on unpublished Placer gamma logs from the Small Syncline). Carr (1981) identified possible relict glass shards in a single thin section from surface outcrop of an intensely veined feldspar-chert between mine grid points 15705E, 14530N and 15690E, 14760N in the Big Syncline near the Lady Loretta ore deposit. This outcrop, here referred to as "Carr's Tuff", was resampled (Figure 11-4a). Although no incontrovertible glass shards were identified, Page (pers. comm., 1996) extracted euhedral zircons which were dated (see Section 3.2.9).

During this study, another suite of texturally-similar, pale to olive green rocks was collected from the Line 3 Costean in the footwall of the Lady Loretta mine (Figure 11-4f). These beds were labelled as "?tuff" on engineering maps but had not been sampled previously, despite being stratigraphically equivalent to Carr's Tuff. Mason (1994) described these rocks as texturally identical to the pink samples analysed by Carr (1981). In thin section, the samples ranged from 24% to 93% of a micron-sized to finely crystalline quartzo-feldspathic mosaic (Mason, 1994). The trace amounts of other minerals are almost identical to the "tuffs" described by Carr (1981). Page (pers. comm., 1996) confirmed the presence of euhedral zircons. However, in contrast to the pink beds, Mason (1994) reported albitic plagioclase as the dominant feldspar in the green beds. This is the first reported occurrence of a Na feldspar cement from the mine area but Taylor (1973) documented authigenic Na feldspar (all oligoclase, An=10) from pyritic and sideritic facies of the Lady Loretta Formation at Johnson Creek.

Approximately 13 m stratigraphically up section from the Na feldspar-chert beds at the mine, texturally-similar darker olive green beds >3 cm thick that were originally described as chert were found to also contain between about 5% and 25% micron-sized feldspar intimately intergrown with the quartz. XRD analyses confirmed the presence of a Na feldspar at this level.

11.6.2 Interpretation

The pink feldspar-cherts from the Lady Loretta mine have been called "porcellaneous adularia bands" (Carr, 1974), "pinkites", "tuffs", "tuffites" or "tuff marker beds (TMB)" (Carr, 1981; Russell *et al.*, 1976). The genetic terminology was based on analogy with similar beds in the HYC and Mount Isa - Hilton ore bodies and preceded Carr's (1981) identification of relict glass shards. However, the genesis of these beds (and, now, their green counterparts) has been controversial for several decades. Part of the problem is that virtually any unusually coloured, thin bedded, aphanitic to finely crystalline rock has been termed a tuff.

Despite no evidence of contemporaneous lavas in northwest Queensland, there were undoubtedly true subaqueous deposits of airfall pyroclastic ash in each area mentioned above (indicating sporadic volcanic activity over >130 Ma). Widespread thin beds of feldspar-rich subaqueously deposited airfall ash containing relict volcanic glass shards, angular crystal fragments and euhedral zircons are well documented in the McNamara Group. The Lady Loretta Formation contains several examples. Berg (1986) positively identified tuffs from core of the Lady Loretta Formation in the Carrier area: "three (samples) are tuffs with particularly good, though very small, shard textures and other features possibly related to 'nuees ardentes', with evidence indicating subaqueous deposition and contemporaneous formation of carbonate masses. Volcanic sources were of broadly trachytic to rhyolitic composition". These core samples or thin sections were not available for further study. Thin sections of outcrop samples collected by Hutton and Wilson (1984) from near the Seymour River also contained relict shards and are now interpreted as subaqueously deposited pyroclastics.

Problems arise with the interpretation of the much more common feldspar-cherts that do not contain any incontrovertible evidence of a volcanic origin.

Similar feldspar-cherts, also called tuffs at HYC and Mount Isa, have been more intensively studied than the examples from Lady Loretta. At Mount Isa, Croxford (1962, 1964) invoked a volcanic origin (because of the presence of glass shards in some examples) and potash enrichment of initially mainly glassy volcanic debris. Van der Heuvel (1969) favoured a zeolite precursor, formed in an alkaline saline environment. A study by Neudert (1983, 1986) found that the feldspar-chert formed as a result of the alteration of a variety of precursors including volcanic ash-fall deposits, sedimentary beds lacking any volcanic affinity and evaporites. He concluded that, contrary to previous opinion, the presence of feldspar-chert does not, by itself, imply the presence of former volcanic material at Mount Isa.

At HYC, Croxford and Jephott (1972) identified relict volcanic glass shards pseudomorphed in pyrite concretions from within the feldspar-cherts leading to all similar beds being termed "tuffs". Logan (1979) recognised that both albite and K feldspar were involved and that they were zoned with respect to the ore. Muir (1979) studied examples from elsewhere in the McArthur Basin and interpreted these rocks as metasomatically altered claystones similar to those formed in modern hypersaline sabkha environments.

The most comprehensive study of the McArthur Group feldspar-cherts is that of Davidson (1995, in press). He found there was good evidence of a volcaniclastic origin, with both primary airfall and slump-resedimented varieties. However, there is also widespread alkali feldspar metasomatism of many clastic units. He suggested that these may have acted as conduits for K-rich solutions. Isotopic modeling of the HYC examples implicated a cool, saline, meteoric fluid probably derived by evaporitic concentration of impounded seawater (Davidson, 1995). Davidson (in press) also discussed the possible relationship between repeated influxes of saline diagenetic water and the transport of base metals.

In interpreting the pink feldspar-cherts from the Lady Loretta mine, Carr (1981) drew heavily on the earlier work by Croxford (1962, 1964) and van der Heuvel (1969) at Mount Isa. He combined their models, stating that all such rocks in the vicinity of the Lady Loretta mine originally contained volcanic glass. The apparent lack of glass fragments in all but one bed was attributed to a complex diagenetic history of low temperature K metasomatism involving alkaline groundwaters and an intermediate zeolite stage. The cross-fracturing was referred to as a metamorphic foliation. The presence of rounded K feldspar "clasts" within an unaltered matrix were interpreted by Carr (1981) as evidence of reworking of the tuff. Several aspects of this interpretation warrant discussion.

Carr (1981) was sometimes unable to distinguish texturally or geochemically between rocks he termed tuffs and others termed arkoses. He acknowledged that samples he illustrated as Plates 7 and 9 were "texturally and compositionally ... intermediate between the tuffs and arkoses" (p99). The arkoses are coarser-grained than the tuffs but also consist of authigenic K feldspar and quartz crystals with the addition of detrital K feldspar, quartz, muscovite and tourmaline; sometimes with a partly sericitic matrix. Detrital carbonate clasts and organic material are also locally common. The arkoses are more thickly bedded than the tuffs, sometimes with well developed lamination, grading and sporadic crossbedding. On the basis of petrographic observations made during the current study, some of the so-called arkoses are better described as texturally immature sandstones with an authigenic K feldspar cement.

Carr (1981) also reported that K feldspar occurs as chert-like authigenic grains and as an aphanitic authigenic matrix between sulphide minerals in the ore beds. Authigenic K feldspar fills the interstices of pyrite framboids and forms a cement around pyritic lenses. Carr (1981) did not reconcile these occurrences with the proposed genesis from bedded tuffs. Thus, as is the case at Mount Isa and in the McArthur Group, not all pink beds containing authigenic K feldspar are necessarily of volcanic origin. Feldspar metasomatism has affected a variety of precursors including several lithologies in the inter-ore sediments and sandstones (arkoses) throughout much of the Lady Loretta Formation at the mine. As proposed by Davidson (1995), sandstones were the conduits for lateral migration of the brines. These aquifers were extensively K-altered to "tuffs" or "arkoses" or Na-altered to green feldspar-cherts.

Aheimer (1994) studied the cross-fracturing of the pink feldspar-chert beds in unweathered core. The sample shown in Figure 11-4e was collected during the current study and also illustrated by Aheimer (1994). This slabbed core sample clearly shows that a fracture delimits the pink colouration. Thin section petrography and microprobe analysis by Aheimer (1994) failed to identify feldspar in the darker portion equivalent to the pink feldspar-chert. In its unaltered state, this bed would not have been identified as a tuff. It also explains why, at the Lady Loretta mine, the so-called tuffs cannot be correlated between cores less than 30 m apart. Since the fracture contains tectonically remobilised mineralisation, at least some of the feldspar metasomatism post-dated mineralisation and tectonism. A similar origin of preferential K alteration would explain the rounded "clasts" of authigenic K feldspar in an unaltered matrix.

The diffuse tops to most of the feldspar-chert beds can be interpreted as evidence of a buoyant brine. Alternatively, it is more likely that they reflect a vertical variation in the porosity and permeability of fining-up sediments.

Irrespective of the precursor lithology, the feldspar-cherts result from replacement by, and growth of, authigenic minerals presumably during subsurface fluid flow. The fluid(s) involved must be sufficiently saline to stabilise feldspar not illite. The Na- and K-enrichment may reflect separate brines or the thermal evolution of a single brine.

The formation of authigenic K feldspar and the diagenetic albitisation of detrital K feldspar and plagioclase are common diagenetic phenomena in numerous sedimentary basins and also affect volcanic rocks. K feldspar metasomatism can proceed at room temperature given a sufficiently enriched brine (Ben-Baccar *et al.*, 1993). Modeling shows that albitisation is enhanced by increasing temperature up to an optimal temperature range of 120-150°C. Kinetic modeling of this reaction predicts the instability of quartz, which is generally considered a K feldspar albitisation product (Ben-Baccar *et al.*, 1993).

Possible sources of the brines include:

- fluids derived from a volcanic source acting at the surface or in the shallow sub-surface, as advocated by Croxford (1962, 1964) for Mount Isa;
- hydrothermal fluids derived from deep-seated sources, that may or may not be associated with mineralisation;
- the dolomitisation of illitic limestone (Swett, 1968; Brown *et al.*, 1978);
- meteoric or surface brines, probably associated with evaporites (as advocated by Carr, 1981; Davidson, 1995 and Logan, 1979).

Proponents of evaporite-derived brines have drawn on several lines of evidence. The first is the prevalence of authigenic K feldspar associated with major evaporite deposits and modern sabkha environments. The Zechstein evaporite complex is zoned from an inner K-rich zone through an intermediate zone to outer albite. Sonnenfeld (1984) discussed several examples of authigenic K feldspar alteration associated with Triassic gypsum in Germany and from clay intercalations in Devonian evaporites in Canada. Permian low grade metamorphic rocks described by Mostler (1968) were interpreted to have been sabkha sediments. They now consist of interbedded carbonate and anhydrite with up to 70% by volume of authigenic idiomorphic albite.

The second line of evidence is the alteration of volcanic glass to K feldspar in alkaline evaporite lakes. This has been described from the Pleistocene Lake Tecopa and the Eocene Green River Formation and is discussed at length by Carr (1981).

Further evidence comes from studies of the chemistry of Recent lakes and lagoons. For example, Kushnir (1981) measured anomalously high K concentrations that increased with depth in the interstitial brine from a modern sea-margin hypersaline lake. He believed this was produced by the dissolution of detrital feldspars.

Collectively, these examples demonstrate that authigenic feldspar can form from ash-fall volcanic glass in the presence of an alkaline fluid and that a spectrum of authigenic feldspar composition may result *without* any volcanic precursor if evaporite-derived brines are involved.

11.6.3 Summary

Some of the feldspar-cherts in the Lady Loretta Formation were derived from the metasomatic alteration of subaqueously deposited ash-fall pyroclastics. However, not all texturally and geochemically similar rocks necessarily had a volcanic component and these beds should not be universally referred to as tuffs. As discussed in Appendix A12.2 and demonstrated by Davidson (1995), gamma logs respond to the high authigenic K feldspar content, thus showing the metasomatic alteration, and should not be used to infer an original tuff.

Both Na- and K-rich fluid phases were probably involved in the genesis of the feldspar-cherts at the Lady Loretta mine. The fluid conduits were along porous and permeable beds such as sandstones and were locally fracture-controlled. The source of the fluids is unknown, but low temperature brines possibly associated with evaporites is favoured for K metasomatism. The Na alteration appears to be of more limited extent and an evolved or separate fluid may be involved in its formation. There does not appear to be a simple zoning of feldspar-chert composition with respect to the Lady Loretta ore body, but further work would be necessary to prove this unequivocally. The timing of feldspar metasomatism at the Lady Loretta mine is largely unconstrained. Migration of brines through sandstones and the possible involvement of evaporites may be interpreted to indicate relatively early timing, but some metasomatism clearly postdates base metal mineralisation and tectonic fracturing.

11.7 METAMORPHISM

Rocks of the McNamara Group are generally described as "sub-greenschist" or "lower greenschist" although, to date, no specific studies have been published to confirm this. Unpublished work (Crick, 1997), based on the degree of organic maturity, placed the limit of greenschist facies metamorphism south of Kamarga Dome, with thermally less mature rocks to the north. It is probable that there are variations both laterally and vertically throughout the McNamara Group, reflecting different burial depths and differing amounts of tectonic strain.

The metamorphic petrology of the Lady Loretta Formation at the mine was studied by Carr (1981) and Etheridge and Lee (1975). Carr (1981) argued that muscovite and chlorite grew metamorphically and that this was evidence of lower greenschist metamorphism. Etheridge and Lee (1975) noted that such mica fabrics were most obvious in the axial zone of the Small Syncline. Their detailed study demonstrated that micas grew preferentially in either, or both, of two orientations. One mica fabric is oriented parallel to bedding and was interpreted as forming "during compaction and diagenesis" (and thus not strictly metamorphic, by definition). The second orientation is parallel to, and defines, the cleavage. This was interpreted as having formed by preferential growth sub-perpendicular to the principal shortening direction during deformation.

Aheimer (1994) described a NaMgFe aluminosilicate (probably a low K stilpnomelane) from the Ore Sequence and interpreted it as product of greenschist facies metamorphism. It occurs in graded layers in an antithetic relationship with first generation pyrite possibly reflecting original sedimentary composition and it commonly lacks any definite shape or crystallographic preferred orientation. Similar stilpnomelane occurs in Mount Isa ore, where Swager *et al.* (1987) interpreted it as having formed by metasomatic silicification of sideritic shale with oriented growth confined to high strain zones.

To date, these metamorphic textures have not been reconciled with the supposed crenulation cleavage defined by closely spaced high angle fractures in some pyrite beds or the locally intense high angle fractures in some feldspar-chert beds. In both these cases, the fabrics do not continue into the surrounding lithologies.

Another approach to evaluating the degree of metamorphism is to study the thermal alteration of organic matter. A sample suite collected for this purpose from the Lady Loretta mine was examined by Crick (NABRE project). In this unpublished work, he expressed the opinion (pers. comm., 1995) that material from the centre of the ore body, although overmature for hydrocarbon production, corresponded to "sub-greenschist" facies. Wilkins (written comm., 1997) used laser raman analysis of carbon from grab samples of the Ore Sequence to obtain a tentative temperature of 250°C that he believed corresponded to the metamorphic maximum.

At the time of writing, a pilot study using illite crystallinity to assess the degree of metamorphism was in progress. The samples were from several formations in the McNamara Group, including the Lady Loretta Formation in the vicinity of the mine and elsewhere. To date, the results are unavailable.

In summary, the Lady Loretta ore body shows evidence of oriented growth of phyllosilicates in areas of highest strain but less evidence of thermal alteration. The textures indicative of highest strain postdate mineralisation.

11.8 SUMMARY OF DIAGENETIC HISTORY

The following diagrams summarise and compare the diagenetic history of the Lady Loretta Formation at two locations and are based on work by Aheimer (1994), Carr (1981) and observations by the author. Much of the timing has been deduced from crosscutting and inclusion relationships. Despite the pertinent new observations presented in this thesis, the least-constrained aspects at the mine remain the origin of the siderite, feldspar-chert and barite (see Section 13.4.9).

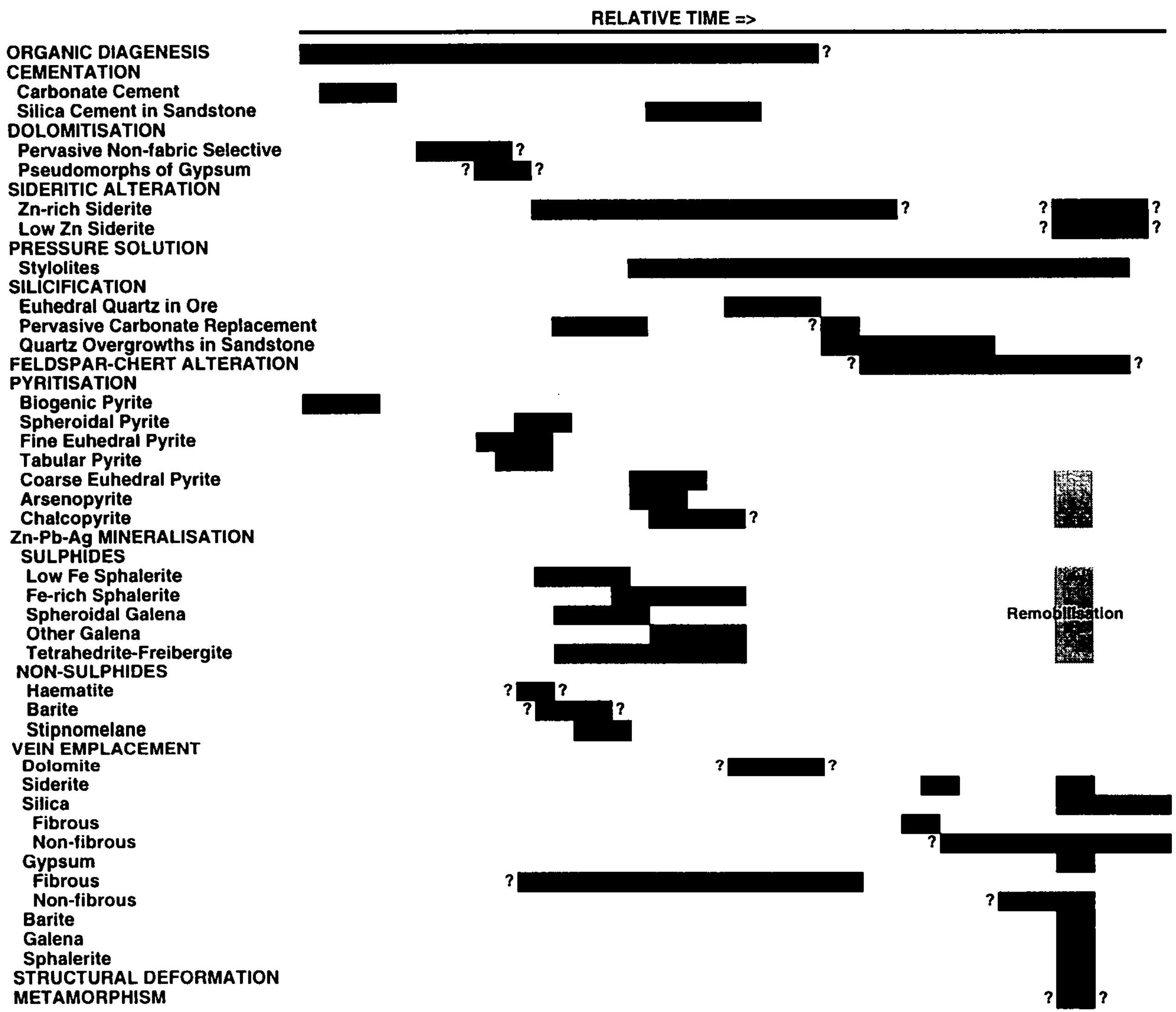


Figure 11-5: Summary of diagenesis and metamorphism in the vicinity of the Lady Loretta ore body.

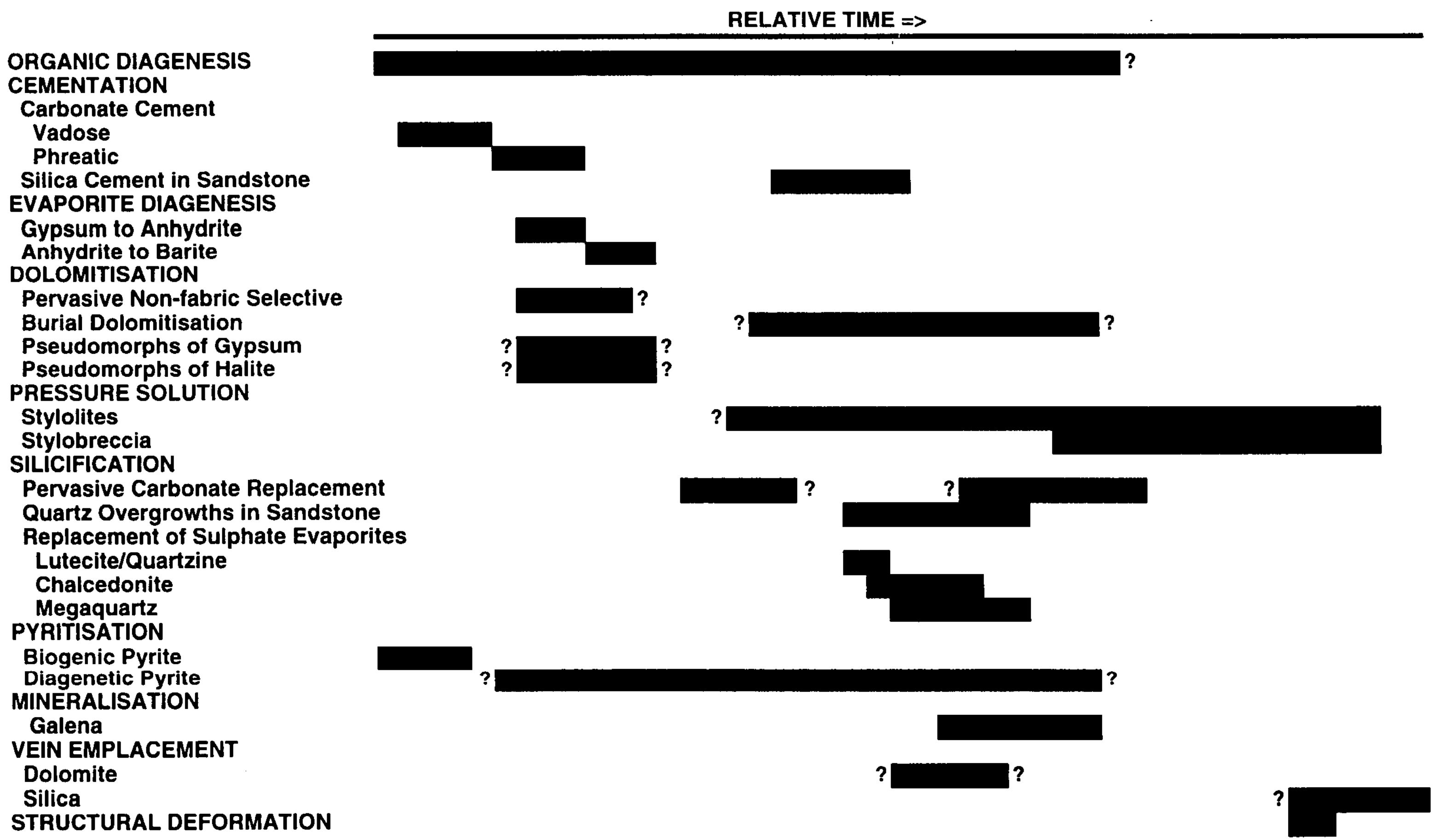


Figure 11-6: Summary of the diagenesis of carbonates at Kamarga Dome.

Chapter 12 - Surficial Processes - Genesis of the "Basal Breccia"

12. SURFICIAL PROCESSES - GENESIS OF THE "BASAL BRECCIA"

12.1 PREVIOUS DESCRIPTIONS

Much of the outcrop of the lower-most Lady Loretta Formation is an enigmatic breccia generally described as consisting of variably coloured, often banded, chert clasts in a fairly homogeneous red-brown cherty, limonitic, to rarely kaolinitic, matrix. Figure 12-1f shows a typical outcrop. The breccia was mapped as an informal lithostratigraphic member, Pml_b, by Sweet and Hutton (1982) on the Lawn Hill Region 1: 100 000 scale geological map. This map shows the breccia to be restricted to the south of the Barramundi Fault on Kamarga Dome and to only occur north of the Termite Range Fault. It was not differentiated on other published maps but was discussed in map commentaries by Hutton and Wilson (1984,1985). Dorrins *et al.* (1983) and Pringle and David (1983) noted its presence in several unmapped localities in the Brenda Creek and Carrier areas and north of Barramundi Fault on Kamarga Dome. Jones (1993) mapped and described the breccia in outcrop adjacent to a southern splay of the Termite Range Fault in the Police Creek area.

Isolated outcrops of this breccia, found to be anomalous in base metals, have been locally referred to as gossans (*e.g.* "Devil's Gossan" at Kamarga Dome) and have been drilled as exploration targets.

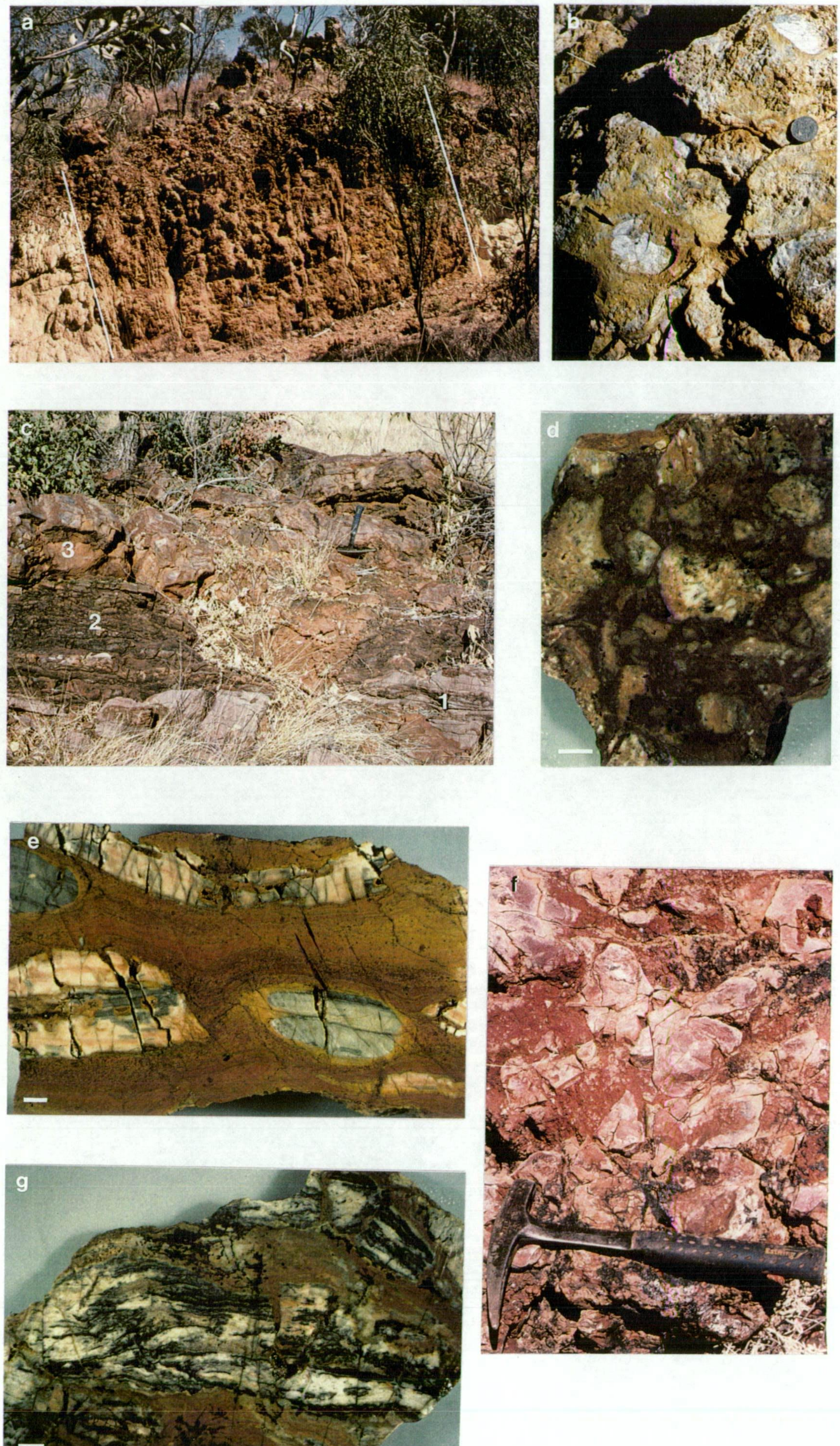
12.2 NEW OBSERVATIONS

12.2.1 Outcrop Scale

This study has shown that the breccia is much more laterally extensive than previously known. Unmapped outcrops occur sporadically over the Lady Loretta Formation on the western and northern flanks of Kamarga Dome. It is locally extensive in both the Phosphate Plant and Redie Creek areas and it can be recognised as far south as Johnson Creek; a total area of over 900 km^2. However, it is absent from the area around Police Creek where shown on the published map. The apparent thickness varies widely over small distances. For instance, it can amount to >250 m of apparent stratigraphic thickness in one location but be absent <100 m along strike. The maximum mapped thickness is in the Cartridge Creek area, where it apparently covers just over 800 m tst. Large apparent thickness changes across faults, as shown on the published map, were in some cases found to be erroneous. In other cases, the thickness variation across the fault was less than along-strike variation away from the fault.

Most significantly, the current study demonstrated than the breccia is not restricted to the lower-most Lady Loretta Formation and is therefore not stratigraphically concordant. The breccia occurs between columnar conical microbialites in the Esperanza Formation at several locations including Police Creek (Figure 12-1b). It is also associated with microbialites in the *upper* Lady Loretta Formation on the northwestern flanks of Kamarga

Figure 12-1: The "basal breccia" duricrust. (a) A costean through the "basal breccia" at Redie Creek. The dip of the beds is indicated by the white lines. Note that the characteristic rounded outcrops of chert breccia do not extend into the subsurface. (b) Chert breccia developed between the columns of columnar conical microbialite in the Esperanza Formation at Police Creek. The unaltered central core of the microbialite is visible in plan (arrowed). Elsewhere in the same outcrop all primary textures have been completely obliterated. (c) Outcrop clearly showing the stages of "breccia" formation. (1) is unaltered dolostone. (2) represents an intermediate stage of brecciation and silicification. (3) shows the typical rounded outcrop of angular chert clasts floating in a ferruginous chert matrix. This exposure is at Kamarga Dome. (d) Typical example of unsorted angular chert clasts in ferruginous chert matrix, Cartridge Creek, CCC133. (e) A texture more like a conglomerate than a breccia, Phosphate Plant, PHP389. (f) Typical outcrop of "basal breccia", Phosphate Plant. (g) Polished slab showing an early stage in development, with original microbial fabric being brecciated in situ by the formation of ferruginous chert material, Phosphate Plant, PHP390. Coin is 3 cm d and bar scale is 1 cm.


a
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Dome (measured section KD6). Measured sections around the flanks of Kamarga Dome confirm that, whereas it is more common lower in the Lady Loretta Formation, the breccia occurs sporadically over the entire formation.

Other observations of the breccia at outcrop scale reveal that the clasts vary dramatically in size within any outcrop and can range from highly angular fragments (Figure 12-1d) to textures resembling nodular bedding (Figure 12-1e). The clasts invariably reflect either the underlying or laterally equivalent facies (silicified clasts of microbial material, thin-bedded dolostone, ooid grainstone and plate breccia were identified); the breccia is never polymict in the sense of sedimentary provenance. Any alignment of clasts seems to indicate that they are essentially *in situ* and in some cases, original textures can be matched between the margins of adjacent clasts. Whereas, the clasts appear to be undergoing *in situ* brecciation, the red-brown matrix is not similarly affected (Figure 12-1g). A complete spectrum from unaltered rock to the typical breccia can be seen at several localities including Phosphate Plant and Kamarga Dome. Figure 12-1c shows unaltered dolostone, grading up discordantly through a partly silicified and brecciated zone to the typical chert breccia.

12.2.2 Thin Section Petrography

Studies of thin sections of the breccia reveal a complex polygenetic history with evidence of both silica solution and reprecipitation. Clasts are commonly highly corroded or gradational to the matrix; others appear to be undergoing *in situ* brecciation. Some clasts exhibit "jigsaw-fit" down to microscopic scale. Where grain to grain contacts occur, the clasts commonly appear to have been originally continuous. Other clasts (commonly in the same thin section) have re-entrants suggestive of dissolution of silica and small ?authigenic inclusion-rich euhedral quartz crystals "float" in the matrix. The matrix contains highly irregular voids and patches of unusual quartz cements including a mixture of length-slow and length-fast quartz and checkerboard chalcedony. Length-fast chalcedony occurs predominantly as spherulites with pseudo-uniaxial extinction crosses. Most early generations of quartz are length-slow.

12.2.3 Subsurface Expression

The subsurface expression of the chert breccia has been variously interpreted. There is considerable evidence that it does not persist at depth and passes to a variety of lithologies. In percussion drillholes in the Kamarga Dome area, the breccia is underlain by, and grades laterally to, highly ferruginised facies within a deep weathering profile. Costeans dug through the breccia in the vicinity of Redie Creek show that it does not persist in the subsurface (Figure 12-1a), at least locally. Cored drillholes intersected either a pyritic shale (Nutter, 1976) or sideritic dolomite (Taylor, 1973) at depth beneath the breccia.

There is some contradictory evidence to indicate that the breccia does extend into the subsurface. Jones (1979) reported several beds of a similar breccia from about 30 m to 80 m subsurface (and below the depth of oxidation) in drillhole KD15 at Kamarga Dome.

However, the breccia is only poorly developed at the surface projection of this interval and the subsurface intersection is in an intensely faulted area. A decimetre-thick intersection of superficially similar breccia, also associated with a fault, was cored at a depth of >100 m by North Exploration on the southern flanks of Kamarga Dome. This breccia is in the Esperanza, not Lady Loretta, Formation.

12.3 PREVIOUS INTERPRETATIONS

Previous interpretations for the origins of this breccia included subaerial sedimentary facies associated with uplift or intraformational erosion. Alternative interpretations invoked a weathering event, either as an intraformational palaeoweathering surface, or during a subsequent exhumation of this stratigraphic level. These explanations have important implications for the tectono-sedimentary interpretation of the Lady Loretta Formation and warrant discussion in light of the new observations presented above.

12.3.1 Sedimentary

The sedimentary models include:

- alluvial fans shedding off uplifted Esperanza Formation (Jones, 1993)
- debris flows associated with the uplift of Kamarga Dome or activity on Termite Range Fault and its southern splays (Dorrins *et al.*, 1983; Jones, 1993)
- sedimentary back-barrier breccia produced by desiccation and brecciation of Esperanza Formation microbialites during exposure and subsequent reworking during barrier flooding events (Harris, 1993).

12.3.2 Weathering

Previously proposed weathering models include:

- a weathering or solution feature related to progressive diagenetic silicification of dolomite (Hutton and Wilson, 1984)
- weathering of a major pyrite zone (Hutton and Wilson, 1985)
- lateritic alteration of a major siderite zone as advocated by Pringle and David (1983) and Taylor (1973); the latter described outcrop and core at Johnson Creek in what was then undifferentiated Paradise Creek Formation (now assigned to Lady Loretta Formation).

12.4 ORIGIN AS A DURICRUST

Evidence collected during this study indicates that a sedimentary origin for the breccia can be disregarded because:

- the breccia does not continue as a sedimentary package into the subsurface
- the large apparent thickness variations are inconsistent with a sedimentary origin
- on a regional scale, the non-stratiform, non-concordant distribution cannot be explained by a sedimentary origin
- the breccia transgresses bedding locally
- the clasts commonly exhibit jigsaw fit and have not been transported.

This study proposes that the "basal breccia" is a duricrust. A duricrust is a hard, resistant regolith layer composed of silcrete, ferricrete, calcrete or any combination of these elements. Duricrusts are also known as pedocretes. Brückner (1966), Ollier (1988, 1991a,b) and Twidale and Milnes (1983) describe duricrusts and the theories of silcrete and ferricrete formation.

There are several key observations that indicate that the "basal breccia" is a duricrust with affinities to both a silcrete and a ferricrete. The textural evidence indicates formation *in situ* by brecciation and silicification of a diverse range of host lithologies with ferruginous material concentrated in the matrix. The examples from the Lady Loretta Formation are similar to coexisting silcrete and ferricrete from several localities in Australia including samples described as a silcrete conglomerate (Langford-Smith, 1978). This consists of chert pebbles in a limonite matrix and the matrix has "impregnated the outer margin of the pebble". Petrographically, the breccia is similar to examples of duricrust described in the literature (Langford-Smith, 1978; Summerfield, 1983a,b); and features such as spherulites with pseudo-uniaxial extinction crosses and checkerboard chalcedony are typical of silcrete. It may be significant that the examples from the Lady Loretta Formation occur in the region of overlap between silcrete-dominant central Australia and the ferricrete concentrated in the moister periphery (see distribution maps in Langford-Smith (1978) and Goudie (1973)). There is evidence of silcrete formation capping other Proterozoic formations in the area. More typical terrazzo-type silcretes cap arenaceous facies of both the Shady Bore Quartzite, especially in the area south of Gundaria Bore.

Thus, the "basal breccia" to the Lady Loretta Formation is interpreted as a surface duricrust. It has features in common with both silcretes and ferricretes elsewhere in northern Australia. It caps a range of precursor lithologies and most commonly occurs in proximity to facies that would provide a silica source such as the cherts of the Esperanza Formation or the orthoquartzites of the Shady Bore Quartzite.

12.5 BASE METAL AND TRACE ELEMENT GEOCHEMISTRY

Numerous company reports document anomalous base metal concentrations from the "basal breccia" to the Lady Loretta Formation. It seems to be regionally anomalous in metals, but locally it can be sufficiently enriched to encourage follow-up exploration. Isolated outcrops have been mapped as "gossans" and dozens of RAB holes have been drilled through and beneath the breccia to test for the presence of economic mineralisation at depth.

The duricrust south of Police Creek is anomalous in Cu and Zn, with up to 2600 ppm Cu and 390 ppm Zn, similar to Wangunda with levels up to 2350 ppm Cu and 245 ppm Zn. Outcrops in the vicinity of Cartridge Creek contain up to 1150 ppm Cu and 290 ppm Zn (Pringle and David, 1983). All these data are up to 200 times background levels from elsewhere in the Lady Loretta Formation in the same areas. At Johnson Creek, Taylor (1973) demonstrated that Cu was relatively enriched in the duricrust by a factor of 10-100 times. Concentrations of Ag and Cr are also significantly enriched relative to background.

Studies by Taylor (1973) and Dunster and McConachie (in press)* both concluded that the colloidal hydrated iron oxides would readily scavenge metal cations from waters and decomposing shale or carbonate minerals. This would give rise to anomalous concentrations of metals and trace elements in the duricrust that are not indicative of economic mineralisation in the subsurface.

The comparative geochemistry of the duricrust and true gossans is the subject of on-going research (McGoldrick and Dunster).

12.6 DISCUSSION

This study has demonstrated that the basal breccia to the Lady Loretta Formation is not sedimentary and speculation about intra-formational regional uplift can be discounted. If it is accepted that the breccia is a duricrust, this raises several interesting points worthy of further work, but beyond the scope of the current study.

12.6.1 What is the Significance of the Host Lithology?

Although the duricrust forms on a wide range of precursor lithologies; theoretically at least, some host lithologies should be more prone than others. For example, the convolute domal microbial fabric should be an ideal candidate, since it contains an intimately mixed source of both silica and iron in the form of interbedded chert and pyrite.

12.6.2 Is It Really Present in the Subsurface?

The two intriguing reports of a similar texture at considerable depth at Kamarga Dome need to be investigated. Given that one occurs in the Lady Loretta Formation and the other in Esperanza Formation, how are they genetically related? They may indicate that a more recent surface weathering event has overprinted intraformational exposures. However, it is probably significant that they are both associated with faults. Perhaps similar textures can result from the subsurface movement of silica and iron as advocated elsewhere by Brückner (1966), Summerfield (1983) and Hesse (1990). If it can be demonstrated that they formed in a similar way to the surface samples, it may have implications for current theories of duricrust formation.

12.6.3 When Did The Duricrust Form?

Since it is not stratigraphically concordant, the duricrust cannot be an intraformational event and it is clearly post-deformational. As described in Section 3.2.6, parts of the Lady Loretta Formation were exposed and weathered during the Cambrian, Mesozoic and several times during the Cainozoic to present. Any one (or combination) of these might have produced a duricrust. The duricrust may be amenable to dating using electron spin resonance technique, as used by Radtke and Brückner (1991).

Chapter 13 - Zinc - Lead - Silver Mineralisation

13. ZINC-LEAD-SILVER MINERALISATION IN THE LADY LORETTA FORMATION

13.1 INTRODUCTION AND DEFINITIONS

13.1.1 Introduction

This chapter briefly examines the economic ore at the Lady Loretta mine and compares it to other occurrences of base metal mineralisation elsewhere in the Lady Loretta Formation and to the other major SSHBM ore bodies in the north Australian zinc belt.

13.1.2 Definitions

Literature discussing models of mineralisation commonly cites the definitions of "syngenetic", "diagenetic" and "epigenetic" from Tourtelot and Vine (1976), as given (slightly modified) below:

"Syngenetic" - minerals deposited or formed simultaneously with the enclosing sediment.

"Diagenetic" - post-depositional formation of new minerals as a result of reactions between the original sediment constituents (detrital or chemical); and interstitial fluids or gases from within the sequence. By definition, the ingredients to make the new minerals were present in the sedimentary sequence at the time of deposition.

"Epigenetic" - post-depositional formation of new minerals, especially ore minerals, by reaction between the original sediment constituents and solutions from an external source.

These terms are not without their ambiguities, since they have different meanings in sedimentology, studies of carbonate diagenesis and economic geology. As also pointed out by Fontbote (1981), the "syngenetic" (syn-sedimentary) mineralisation of carbonate could be contemporaneous with the "diagenetic" formation of the host dolomite. Furthermore, "diagenetic", when used in the sense of Tourtelot and Vine (1976), does not have the same meaning as the adjectival form of "diagenesis" (*sensu* Chapter 11) which applies to *all* processes affecting a sediment excluding subaerial weathering and metamorphism. Indeed, the "diagenetic" definition from Tourtelot and Vine (1976) hinges on the interpretation of the phrase "from within the sequence". It is unclear whether this refers to a bed or a basin or anything between. Does the "external source" required for epigenetic mineralisation imply an extra-basinal fluid?

"Sedimentary exhalative (SEDEX)" as originally defined by Large (1980, 1983) was limited to metalliferous *marine* sediments. This led Eugster (1987) to extend the definition to discriminate between continental and marine SEDEX mineralisation.

Thus, many of the commonly used terms can be ambiguous. The following definitions indicate in what sense these terms are being used in the current study.

In deference to the longer-standing definition of "diagenesis", the following discussion will not refer to "diagenetic" mineralisation.

"Syngenetic" is taken to mean that the majority of mineralisation is occurring at the sediment/water interface. This includes "SEDEX" in the sense that it is usually used and does not imply either a marine or non-marine setting. Nor does it imply any genetic source of the fluids involved.

"Early epigenetic" refers to the majority of mineralisation occurring in the shallow subsurface in unlithified sediments. This may be accompanied by subordinate "syngenetic" mineralisation if the mineral-bearing fluids reach the top of the sedimentary profile.

"Late epigenetic" is taken to mean mineralisation occurring within lithified rocks.

13.2 DESCRIPTION OF MINERALISATION IN THE LADY LORETTA FORMATION

13.2.1 Uneconomic Mineralisation away from the Mine

Sub-economic and trace Zn-Pb-Ag mineralisation is known from several locations in the Lady Loretta Formation. Visible Pb and Cu minerals occur within cauliflower cherts from Kamarga Dome and are described in Section 11.4.5. The following discussion focuses on anomalous Zn and Pb reported from highly pyritic carbonaceous dolomitic siltstones and shales in the Tom Cat and Carrier areas.

The objectives of this review are to, where possible, determine:

- the timing of this mineralisation
- if there are small-scale analogues for the stratiform and stratabound Lady Loretta ore body, particularly for the laminated and thin bedded nature of the ore
- if there is a consistent relationship between the nature of the host rocks and the style of mineralisation.

Tom Cat

The Tom Cat area, approximately 6 km to the northeast of the mine and across Western Border Fault, contains a continuation, or direct correlatives, of many of the units recognised in the Lady Loretta mine. This was originally documented by Donaldson (1985) and is demonstrated in more detail in Section 10.3.4 of this study. The Ore Sequence Equivalent, termed the Massive Pyrite in Donaldson (1985), is present between 333 and 362 m tst in core from drillhole LA64. Pyrite is ubiquitous in the upper 10 m and both bedded laminated and euhedral epigenetic forms are present. The distinctive pyrite texture, resembling a crenulation cleavage that does not extend into the surrounding rocks, is present both in LA64 and the ore body. The sedimentology is similar to both the ore host rocks and Pyritic Unit at the Lady Loretta mine. Fluidisation features, possibly associated with dewatering, were noted from the same stratigraphic interval at both locations. Most of the visible mineralisation in the LA64 core is sphalerite. It occurs within the upper portion of the Ore Sequence Equivalent as lithostratigraphically defined, and extends into the overlying Cyclic Unit. Some sphalerite occurs as diffuse patches of replacement within dolomitic siltstones and there is textural evidence of sphalerite replacing both euhedral and bedded pyrite. The majority of the visible mineralisation is, however, clearly epigenetic and associated with tension gashes and veins.

Carrier Area

One of the best documented examples of sub-economic mineralisation in the Lady Loretta Formation was intersected in drillholes CRD1-5 is in the Carrier area, approximately 80 km north of the mine. The following description is from Berg (1986) who reported anomalous stratiform Zn-Pb (up to 2100 ppm Zn and 620 ppm Pb) mineralisation concentrated in two stratigraphic units. These intervals may be at approximately the same lithostratigraphic level as the Lady Loretta ore body based on the thicknesses to the Esperanza Formation and Shady Bore Quartzite. Although tuffs were identified in core form the CRD holes, samples for dating were not retained and the chronostratigraphic relationship to the ore body is unclear.

The upper unit described by Berg (1986) consists of a 10 m thick pyritic package (of which 6 m is >10% pyrite) overlying highly carbonaceous siltstones and altered silty carbonates. Possible microbial fabrics were described from the pyritic unit. This is overlain by K feldspar-cherts (at least one of which is a true subaqueously deposited ashfall), sideritic siltstones and regular alternations of carbonaceous shale and fine grained clastics with convolute bedding and small-scale slumps. The surface expression of the pyrite layer is a thin stratiform ironstone (with up to 1000 ppm Pb) that can traced for over one kilometre along strike. Mineralisation is concentrated in thin beds within and below the pyritic zone. Thin discordant sphalerite veins are also present.

The lower mineralised sequence contains only weakly anomalous Zn-Pb values and is associated with thin beds of laminated pyrite and silicified microbialite. Mineralisation is mainly confined to fractures and trace levels of chalcopyrite are present. This is underlain by sandstones and laminated cherts that are in turn underlain by variably ferroan dolomites with large gypsum pseudomorphs. Unusual thin breccias similar to the inter-ore breccias at the mine occur in the carbonaceous siltstones that separate the two zones of anomalous mineralisation. Disturbed bedding that can be interpreted as a fluid injection feature is also present. The overall physical similarity to the Lady Loretta ore body is striking, but there are equally important differences.

Although broadly stratiform and stratabound, very little of the visible Zn-Pb mineralisation in the Carrier area was described as well laminated and the laminated mineralisation is confined to bedded pyritic facies. There is proportionally more obviously epigenetic mineralisation associated with fractures and veins than at the Lady Loretta mine.

A comparison of the geochemistry shows similarities with the mine (Figure 13.1). The significance of Fe- and Mn-rich carbonates at both localities is discussed in Appendix A-8. Although Berg (1986) did not mention barite, it is interesting to note that his analyses of three of the laminated pyrite intersections in the upper mineralised sequence have percent levels of Ba. As pointed out by Beeson *et al.* (1989), K is also anomalous in this facies, ranging from 2.2 to 7.8%. The geochemistry of pyritic carbonaceous shales from the Pyritic Unit at the mine (2660P134 253.9 m) and the Carrier area (CRD-1 320756) are very similar, even to the extent of their trace Zn-Pb mineralisation. There is no statistical difference between the population of Zn numbers (100 Zn/(Zn+Pb)) from the Carrier area and those from the Lady Loretta mine. Carbonate compositions in both areas are similar (see Appendix A-8). However, the Alteration Index (McGoldrick, 1993; Large, 1994) plot of the Carrier data (Figure 13.2) does not indicate ore-grade mineralisation.

Summary

The data presented above, and elsewhere in this thesis, can be interpreted to indicate that the following points are important for base metal mineralisation in the Lady Loretta Formation:

- bedded pyrite is ubiquitous in highly carbonaceous facies that host anomalous Zn-Pb mineralisation in several areas
- anomalous Zn-Pb mineralisation occurs in sedimentologically similar facies, interpreted to represent shallow water deposition
- siderite and other unusual carbonates occur as diagenetic alteration in association with carbonaceous pyritic shales, both associated with, and independent of, mineralisation (see Appendix A-8)
- in several cases, there are no obvious large fault feeders for fluids
- sub-economic mineralisation and the ore grades at the mine share a similar statistical distribution of Zn numbers, but the Alteration Index is a reliable indicator of economic mineralisation
- some Cu mineralisation appears to be independent of Zn-Pb mineralisation, visible Cu mineralisation appears to be late epigenetic away from the mine
- galena replaces Ca evaporites (or their pseudomorphs) in cauliflower cherts from the Kamarga region.

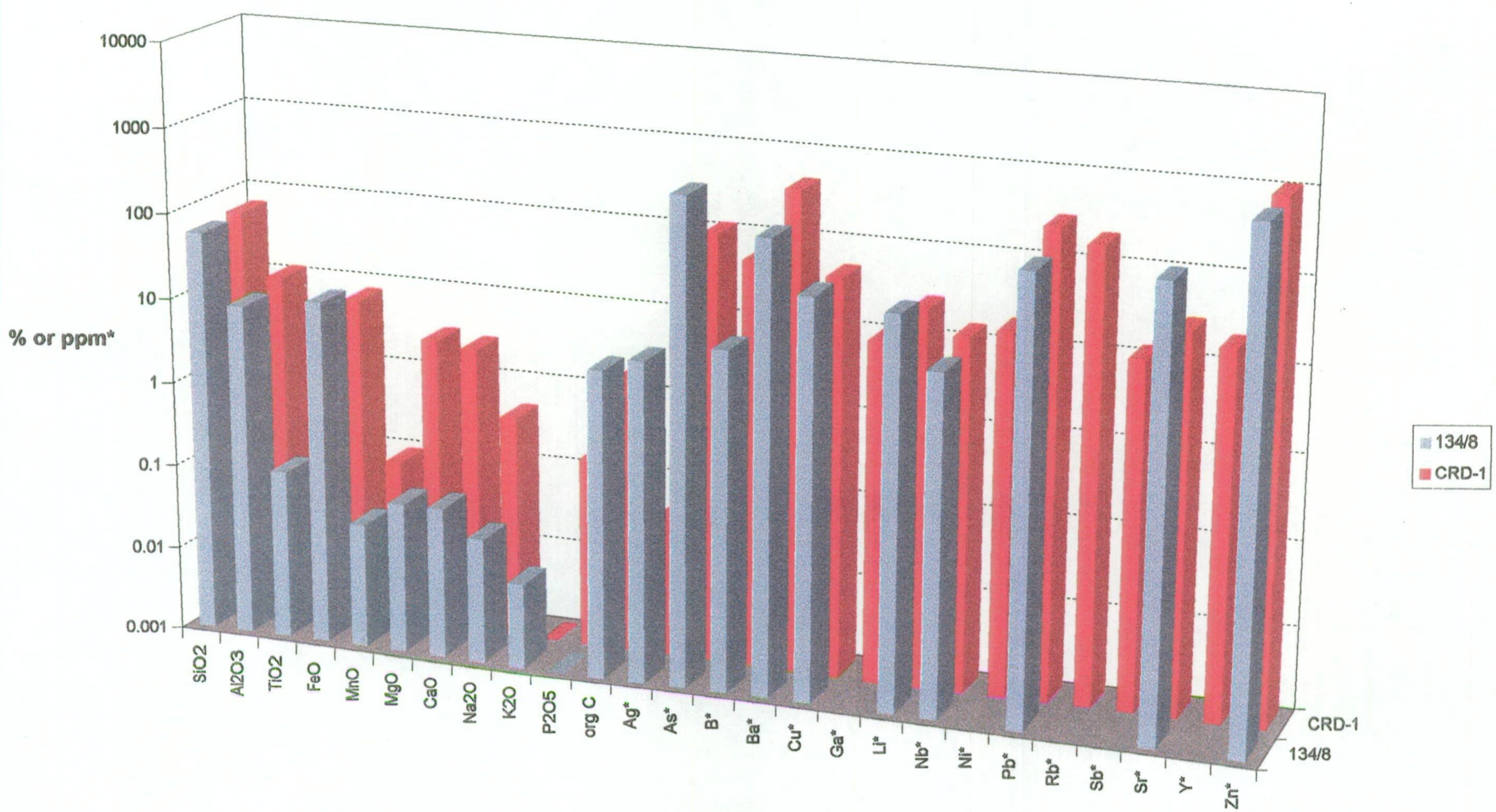
13.2.2 The Lady Loretta Ore Body

The Lady Loretta ore body contains thin bedded to laminated ore consisting of 10-50 μm Zn-Pb-Ag sulphides. Compared to the Mount Isa ore bodies, there are relatively few cross-cutting sulphide veins at Lady Loretta and these are mostly remobilised galena. The ore textures at Lady Loretta have been described in detail by Carr (1981), Aheimer (1994), McGoldrick (1993) and McGoldrick *et al.*, (1993, *et seq.*). The following discussion focuses on those features that can be directly compared to subeconomic and trace mineralisation elsewhere in the Lady Loretta Formation or to the other SSHBM ore bodies of the northern Australian zinc belt.

13.3 COMPARISON OF THE LADY LORETTA MINERALISATION WITH OTHER ORE BODIES OF THE NORTH AUSTRALIAN ZINC BELT

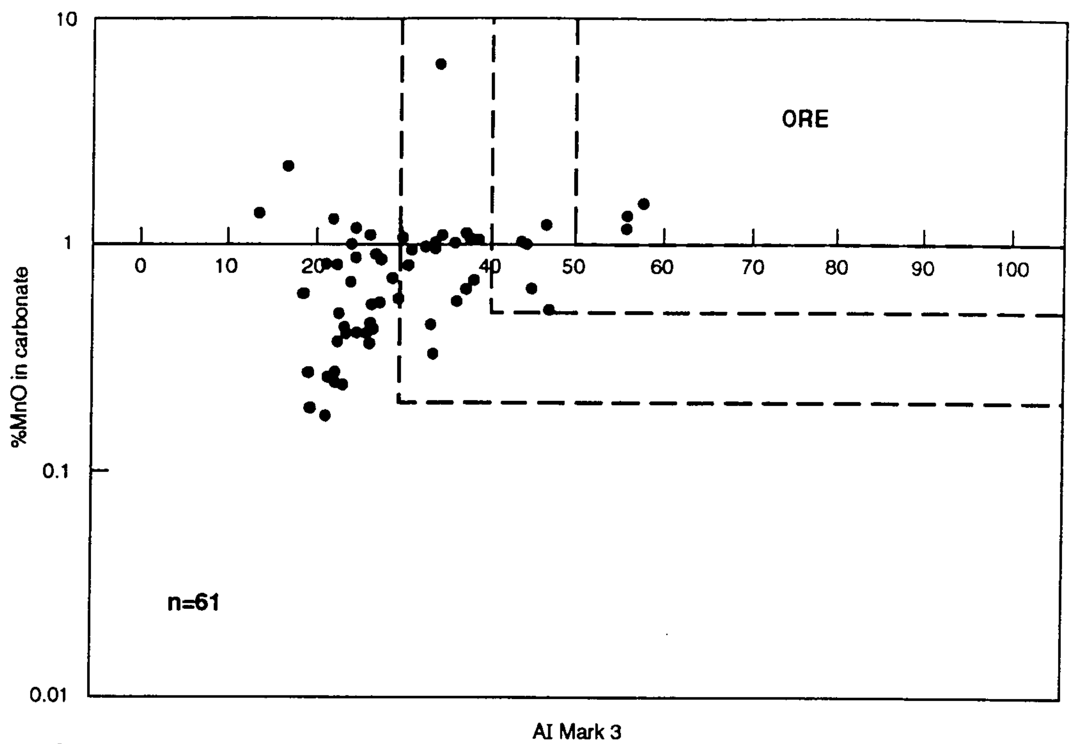
Table 13-1 compares the salient features of the SSHBM ore bodies and major prospects in the north Australian zinc belt and the tonnages versus grades are shown in Figure 13-3.

Figure 13-1: Comparison of geochemistry of shales from the Pyritic Unit at the Lady Loretta mine (2600P134, 253.9 m) and the Carrier area (CRD-1, sample 320756).



10000
1000
100
10
% or ppm*
1
0.1
0.01
0.001
SiO2
Al2O3
TiO2
FeO
MnO
MgO
CaO
Na2O
K2O
P2O5
org C
Ag*
As*
B*
Ba*
Cu*
Ga*
Li*
Nb*
Ni*
Pb*
Rb*
Sb*
Sr*
Y*
Zn*
CRD-1
134/8
134/8
CRD-1

Figure 13-2: The MnO_D and Alteration Index calculated for carbonates of variable composition in the Carrier area (see Appendix A-8).


10
1
0.1
0.01
%MnO in carbonate
0
10
20
40
50
60
70
80
90
100
ORE
n=61
AI Mark 3

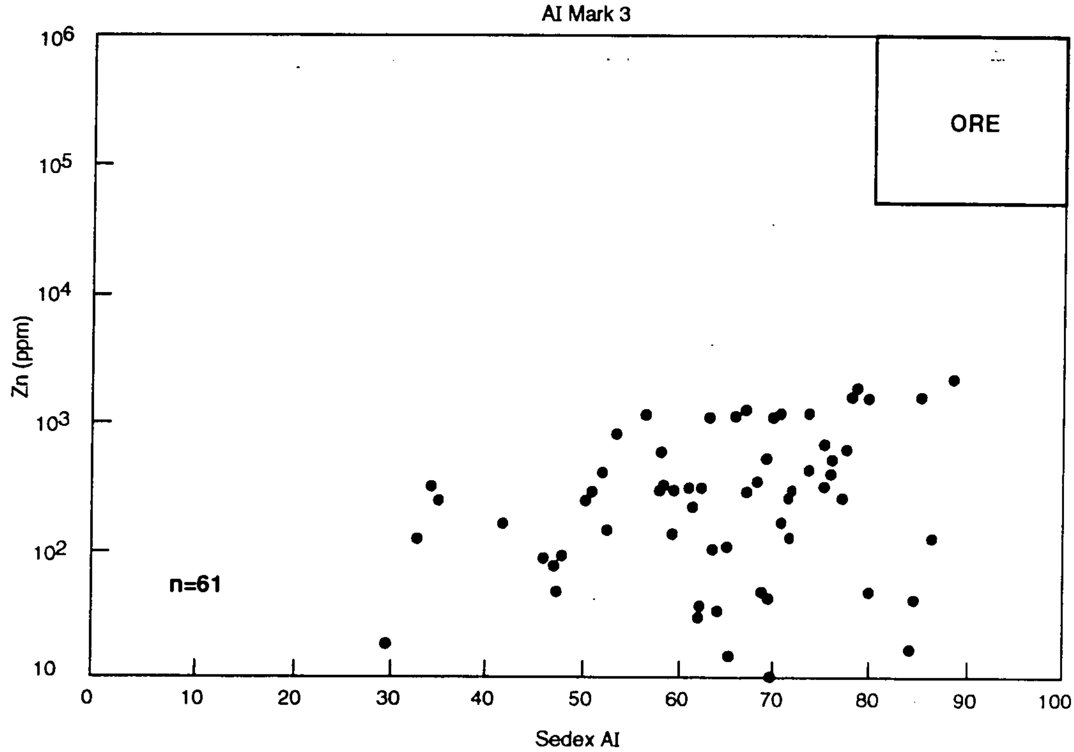
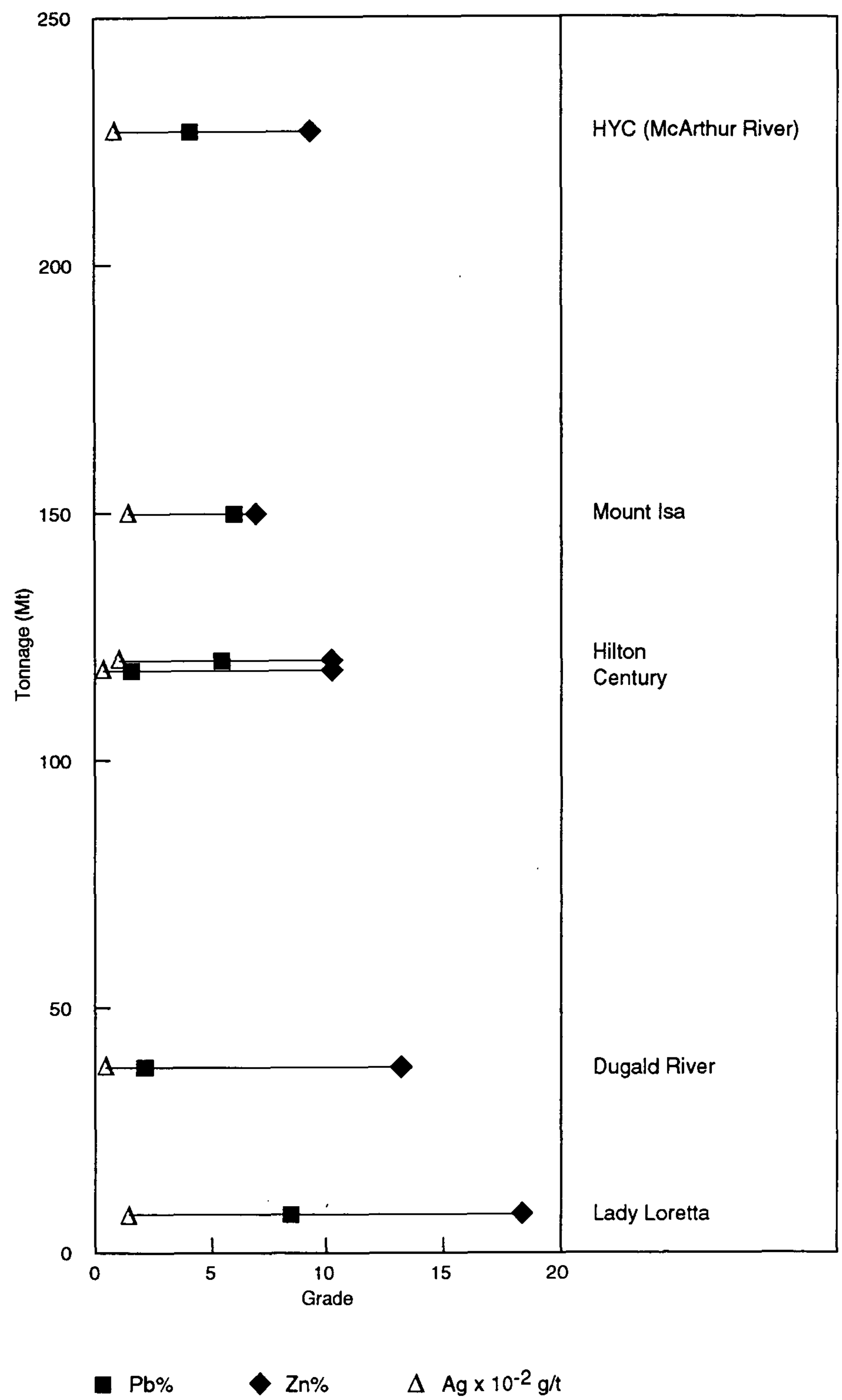

10^6
10^5
10^4
10^3
10^2
10
Zn (ppm)
ORE
n=61
0
10
20
30
40
50
60
70
80
90
100
Sedex AI

Table 13-1 (fold-out): The salient features of the SSHBM ore bodies and major prospects in north Australian zinc belt. Modified from unpublished work by McGoldrick for the AJES thematic issue which also contains the original references.

Ore Body	Tonnage	Grade Zn%, Pb%, Ag g/t	Mineralisation	Host Rocks	SHRIMP Zircon Age of Host Unit (Pb model age)	Metamorphism & Deformation	Evaporites	Oxidised Sediments	Zoning	Halos
HYC (McArthur River)	8 ore lenses in 70 m total res. 227 Mt; current project 104 Mt	9.2 Zn, 4.1 Pb 14.1 Zn, 6.1 Pb, 60 Ag	stratiform, f.g. py, sp, minor cpy, marcasite, ars; primary textures well preserved	Barney Creek Fm - HYC Pyritic Shale; pyritic, organic rich (up to 7% TOC), dolomitic siltstones; coarse sedimentary breccias; minor tuffaceous component	1640±3 Ma (*ca.* 1640 Ma)	essentially unmetamorphosed; basin inversion, but no penetrative deformation	important part of sequences above & below HYC Pyritic Shale are evaporitic	W-Fold Shale below mineralisation has extensive patchy reddening; Emu Fault; various units elsewhere in McArthur & Tawallah Gps	small very Cu-rich zone in the north; general (Cu-)Pb-Zn	pyrite; Tl regionally; Fe & Mn in carbonates: C & O isotopes
Walford Creek	no published reserve; several ore-grade intersections covers an area of 1.5 x 6.0 km in plan	a few metres Cu, Zn, Pb	3 stacked lenses of stratiform massive py with sp & ga as a matrix in pyritic beds; primary textures preserved	Fickling Gp - Mt Les Siltstone; dolomitic shale (regionally), highly carbonaceous, dolomitic & pyritic shales & local talus breccias	1640±7 Ma	subgreenschist; relatively flat-lying, but bounded by a major regional structure (Fish River Fault)	pseudomorphs after gypsum in Mt Les Siltstone		Cu-rich, late stage mineralisation near Fish River Fault	
Century	2 main ore zones in a 40 m mineralised sequence; 118 Mt	10.2 Zn, 1.5 Pb, 36 Ag	stratiform sp, py (5-10%), ga ± cpy (intimate association with organic matter & authigenic silica); primary textures are preserved	McNamara Gp - Lawn Hill Fm - unit Pmh4; siliciclastic, carbonaceous (TOC 1 - 5%), sideritic, shales & siltstones; minor tuffaceous component	1595±6 Ma (1575)	subgreenschist; open folding, faulted ore contacts; stylolitic layering in ore sequence			highest Zn grades transgress the mineralised sequence from SE to NW	py envelope; intense siderite development in siltstones
Lady Loretta	single high grade lens <50 m thick & is recognisable over several km2; 8.3 Mt	18.4 Zn, 8.5 Pb, 125 Ag	stratiform py, sp, ga, tetrahedrite, barite, silica , tr. hem; some primary textures preserved	McNamara Gp - Lady Loretta Fm; carbonaceous, pyritic, dolomitic, sideritic siltstones & shales	1647±4 (<1600 & >1570 Ma)	?subgreenschist; open - tight synclinal structure locally, more open folding regionally	gypsum moulds from ore horizon; halite casts strat. higher, evaps common in north of Lady Loretta Fm	Trent to west of mine	Pb-Zn centre to Zn-Ba-chert on flanks of main mineralisation	py, siderite, Mn, Tl; C & O isotopes
Grevillea	no published reserve; several ore-grade intersections	Zn, Pb	stratiform massive py & barite; sp & ga in pyritic beds	McNamara Gp - Riversleigh Siltstone; siliciclastic carbonaceous mudstone & sandstone	<1647 & >1636 Ma	?subgreenschist; relatively flat-lying, fault-bounded	no known evaporites in Riversleigh Siltstone	sandstone interbeds, & basal Shady Bore Quartzite		
Mount Isa	30 stacked (en echelon) ore lenses in 1000 m (most in upper 650 m); pre-production reserve of *ca.* 150 Mt	7 Zn, 6 Pb, 150 Ag	stratiform py, sp, ga, tetrahedrite ± po, rare mte; ores show locally intense deformation, but some primary textures are preserved	Mount Isa Gp - Urquhart Shale; carbonaceous (now graphite), pyritic, dolomitic siltstones; important 'tuffaceous' component	1652±7 Ma (1653-1654)	(?lower) greenschist facies	pseudomorphs of gypsum; halite casts in siltstone unit above Urquhart Shale	basal Mt Isa Gp; Surprise Creek Fm (beneath & possibly lateral equivalent to Mt Isa Gp)	(Cu-) Pb - Zn	pyrite; Tl; ?Fe, Mn enrichment in carbonates
George Fisher	8 stacked ore lenses; *ca.* 68 Mt	5.8 Pb, 12.5 Zn, 92 Ag	as for Mt Isa	as for Mt Isa	as for Mt Isa	as for Mt Isa	pseudomorphs in orebodies interpreted to be after primary sulphate evaps	as for Mt Isa		
Hilton	7 stacked ore lenses; *ca.* 50 Mt	9 Zn, 6.5 Pb, 150 Ag	as for Mt Isa, but with higher grade & more Cu-rich fault-related ore	as for Mt Isa	as for Mt Isa	as for Mt Isa, but locally more structurally complex		as for Mt Isa	upper ore bodies most Cu-rich; (Cu) Pb-Zn moving up-dip	sideritic siltstones
Mount Novit	single pyrite lens up to 20 m thick; strike length of 5 km; no calculated resource, several intersections of >10% Zn+Pb		stratiform/stratabound (massive) crs py, po, mte ± sp, ga	lower Mt Isa Gp - Moondarra Siltstone; dolomitic, pelitic schists	<1660 & >1650 Ma; i.e. slightly older than Urquhart Shale	greenschist/amphibolite transition; complexity due to faulting		as for Mt Isa		siderite in mineralisation
Dugald River	40 m thick lode; 38 Mt	13.2 Zn, 2.1 Pb, 32 Ag	stratabound py, sp, po, ga, tr. cpy, pyrargyrite, ars, tetrahedrite; mostly recrystallised, but some rare primary textures	Dugald River Slates (Shear Zone) - black, carbonaceous slates; stratigraphic position is not well constrained	uncertain, but probably older than Mt Isa Gp, (Pb older than Mt Isa)	greenschist/amphibolite transition; re-folded isoclinal folds with mineralised sequence overturned; mineralisation has mylonitic contacts	Corella Fm in stratigraphic footwall is scapolite-rich; pseudomorphs after ?shortite from the mineralised sequence	? late hematitisation of Corella Fm in the stratigraphic footwall	(Cu-) Pb - Zn & S isotopes	K, Li, Rb, Tl, Pb, Se, Ag, & Sr enrichment in hanging & footwall

Figure 13-3: Tonnage versus grade for the major SSHBM ore bodies in the north Australian zinc belt. Note the relatively lower tonnage but higher grade quoted for the Lady Loretta ore body.


250
200
150
100
50
0
Tonnage (Mt)
0
5
10
15
20
Grade
HYC (McArthur River)
Mount Isa
Hilton
Century
Dugald River
Lady Loretta
Pb%
Zn%
Ag x 10-2 g/t

13.4 KEY ELEMENTS OF A GENETIC MODEL FOR THE LADY LORETTA ORE

13.4.1 Timing of Mineralisation

Introduction

Despite decades of research, the timing of mineralisation in the north Australian SSHBM ore bodies remains contentious. As discussed in Section 13.5, proponents of syngenetic and epigenetic models have appealed to various lines of often contradictory textural and isotopic evidence to argue their case. In the case of the Lady Loretta ore body, an age obtained from zircons in tuffaceous sediments collected during this study will be compared to the Pb isotopic age of galena from the ore.

Pb Isotopes and Pb Model Ages

The Lady Loretta mineralisation has a significantly larger spread in Pb isotope values than most other ore bodies in the north Australian zinc belt (Table 13.2). This is evident in analyses of individual laminae within the ore (Carr and Gulson, 1984) and from the gossanous surface outcrop of the Ore Sequence Equivalent in both synclines (Vaasjoki and Gulson, 1985). In particular, $^{206}Pb/^{204}Pb$ analyses from Lady Loretta range up to values considerably more radiogenic than the other major ore bodies. Carr and Gulson (1984) noted that the more radiogenic isotopes formed a homogenous population and corresponded to layers of very fine grained mineralisation.

Ore Body	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	Reference
Lady Loretta U/G	2.2099±.0.0050	0.9517±.0.0028	16.257±.0.071	NR	Carr & Gulson (1984)
Small Syncline Surf.	2.2086±.0.0077	0.9501±0.0058	16.291±0.108	15.478±0.014	Vaasjoki & Gulson (1985)
Big Syncline Surf.	2.2076±0.0056	0.9491±0.0034	16.314±0.066	15.484±0.017	
Overall Surface	2.2080±0.0064	0.9495±0.0045	16.305±0.084	15.481±0.016	
Mount Isa	2.2224±0.0013	0.9586±0.0005	16.112±0.013	NR	Carr & Gulson (1984)
Hilton	2.2220±0.0009	0.9587±0.0005	16.120±0.013	NR	
Dugald River	2.2273±0.0015	0.9608±0.0004	16.055±0.004	NR	
HYC	2.2185±0.0012	0.9571±0.0002	16.149±0.009	NR	

Table 13-2: Lead isotopic composition of ore and surface gossan from Lady Loretta compared to other SSHBM deposits in the north Australian zinc belt. Mean and standard deviation are shown. NR means that the ratio was not reported.

Carr and Gulson (1984) interpreted the spread in the data to indicate the existence of two major mineralising fluids during ore formation. Sun *et al.* (1994) thought it "might reflect incomplete homogenisation of Pb derived from sources with different μ values and/or a protracted period of mineralisation (*i.e.* epigenetic)".

The Pb isotope data have also been used to establish ages for the mineralisation in all the large north Australian SSHBM ore bodies including Lady Loretta. Sun *et al.* (1994)

used zircon U-Pb ages of volcaniclastic rocks to calibrate a modified Cumming and Richards Pb growth curve specific to the north Australian zinc belt. Using this curve, the Pb model ages of the majority of the ore bodies agree with the stratigraphic age of the host rocks, supporting a syngenetic or very early epigenetic model of mineralisation. This applies to Mount Isa, Century and HYC. The apparent synchronisity for ore and host at HYC and Mount Isa was verified using the $^{207}Pb/^{204}Pb$ double spike method (Sun *et al.*, 1996).

However, Lady Loretta ore is an enigma. Using the Sun *et al.* (1994) plot, its relatively high $^{206}Pb/^{204}Pb$ data can be interpreted to indicate that the mineralisation is <1600 Ma and possibly as young as *ca.* 1570 Ma. This is significantly younger than the zircon age of 1647±4 Ma for the host rocks.

The most obvious interpretation is that the mineralisation at Lady Loretta mine is late epigenetic; whereas Century, Mount Isa and HYC are essentially syngenetic. It is ironic that the currently popular genetic models for Century and Mount Isa are late epigenetic whereas a syngenetic to very early epigenetic model has been proposed for Lady Loretta. This aspect of Pb isotope dating remains one of the greatest unresolved controversies of the north Australian SSHBM ore bodies.

13.4.2 Source of Zn-Pb-Ag

Introduction

Volcanics are often thought to be the source of the metals in the north Australian SSHBM ore bodies generally (*e.g.* Derrick, 1993; Edwards and Atkinson, 1986; McConachie 1993b) and Lady Loretta specifically (Amade, 1986). However, there are other possibilities. Mass balance calculations have shown that leaching a small fraction of metals present in most sedimentary rocks, particularly shales, can provide sufficient metal for generating ore deposits (Krauskopf, 1967; Vine and Tourtelot, 1970). The presence of widespread evaporite pseudomorphs throughout much of the McNamara Group can be interpreted to suggest that the diagenesis of evaporites could also have contributed metals.

Volcanics

Most previous studies of the source of metals in the Mount Isa Basin have focussed on volcanics and two lines of supporting evidence are invoked:

- the depletion of once metal-rich volcanics in the underlying stratigraphy
- the abundance of so-called tuffs associated with many of the SSHBM ore bodies implying a basin-heating event and the presence of subaerial volcanics contemporaneous with metal precipitation.

As discussed in Section 11.8, not all the so-called tuffs were pyroclastic ash-falls. The true tuffs range over 160 Ma, and as such are not confined to the time of deposition of the ore-host sediments. The tuffs may have been deposited hundreds or thousands of kilometres from the site of volcanic eruption. There are no known contemporaneous sites of volcanic eruption in the Mount Isa Basin.

Volcanics in the rift-phase of the Mount Isa Basin, particularly the metabasalts of the Eastern Creek Volcanics, have a high Cu content and were thought to be the source of much of the Cu mineralisation in the area (Scott and Taylor, 1982; Wilson *et al.*, 1985). Other workers (*e.g.* McConachie, 1993b) also believed that they might have been a source of Zn-Pb-Ag. Analyses of relatively unaltered specimens in Hutton and Wilson (1985) and Wilson *et al.* (1985) show that Zn averages 153 ppm (max 190 ppm) whereas Pb is less than 34 ppm (mean 13 ppm). It is also noteworthy that these rocks contain up to 660 ppm Ba (mean 410 ppm) (see Section 13.4.9).

Re-examination of the analytical data summarised in Wilson *et al.* (1985) confirms that the metabasalts in the Mammoth Mines area are significantly depleted in Cu (by 83% on average), relative to others regionally. Scott and Taylor (1982) argued that this Cu now forms the Mammoth Mines ore bodies. However, the samples that are supposedly depleted in Cu still contain significant quantities of Zn (mean 160 ppm) and up to 30 ppm Pb (*cf.* the regional averages of 153 ppm and 13 ppm respectively). It would appear that if Cu has been stripped from these metabasalts, they did *not* source Zn or Pb at the same time.

The closest volcanic rocks to the Lady Loretta orebody have been faulted up into their present position post-mineralisation and were probably originally >3000 m below the host stratigraphy of the ore body. This chloritic metabasalt contains 55 ppm Zn and 35 ppm Pb. Since the Cu content is low compared to basalts from the Eastern Creek Volcanics, it has been argued that these relatively low values are a result of metals being stripped from the rocks (to source the Lady Loretta Zn-Pb-Ag and/or Lady Annie Cu mineralisation) but it is unclear how this would be distinguished from originally low levels. Furthermore, there is no firm evidence that this volcanic rock has any affinity with the Eastern Creek Volcanics (see Section 3.3) and such comparisons may be meaningless.

The volcanic rocks in the Mount Isa Basin occur in a thick rift sequence (Blake's (1987) cover sequence 2). This is separated from the overlying rocks that host SSHBM mineralisation by a major unconformity. Given the thickness of the rift sequence (>7 km) and assuming a conservative geothermal gradient (37°C/km), it seems likely that the rift-fill reached thermal maturity and expelled its brines long before the overlying sediments were deposited. This is even without allowing for the extra heat provided by the igneous intrusions. Thus, it seems unlikely that brines generated as part of normal basin dewatering could have carried metals from the volcanics in the rift to the host rocks of the SSHBM deposits. Another problem in stripping metals from volcanics and long distance migration of the resulting brines is the nature of the aquifers in a volcanic-dominated terrain. Typically, intra-volcanic clastics are of only local extent and even well sorted coarse clastics are notoriously poor aquifers because of the high content of labile minerals. In the case of the Mount Isa Basin, areas where widespread regional aquifers of the overlying basin phase (*e.g.* Torpedo Creek Quartzite) directly overlie volcanics of the rift-phase are the most likely configuration capable of stripping metals from the volcanics and transporting them regionally. Such a relationship exists at Kamarga Dome, where the Torpedo Creek Quartzite unconformably overlies the Kamarga Volcanics, and this may explain why the Torpedo Creek Quartzite is anomalous in Cu in that region. However, the Torpedo Creek Quartzite is not known to directly overlie volcanics in the vicinity of the Lady Loretta mine.

Sedimentary Rocks

Some of the clastic sedimentary rocks in the Mount Isa Basin will have inherited a high background of metals because they include a significant detrital component derived from the volcanics. However, many sedimentary rocks can act as metal sources independent of any inheritance.

In a comprehensive theoretical study of SSHBM mineralisation, Lydon (1983) concluded that metals were leached from argillites and siltstones especially during the conversion of montmorillonite to illite. The underlying sedimentary strata were seen as the source of metals for the HYC ore body but attempts to prove this using the using Pb isotopes were equivocal (Lambert, 1983). Russell (1983) suggested that the thick sedimentary pile was the source of metals at Mount Isa, although he considered that leaching was from rocks stratigraphically *above* the mineralisation. McConachie (1993b) cited black shales throughout the stratigraphy and sedimentary rocks in the rift sequence as potential sources of metals.

Carr (1981) thought that the metals at Lady Loretta were sourced from the sedimentary rocks of the underlying stratigraphy, particularly the Paradise Creek and Gunpowder Creek Formations. Typical analyses of "barren" Paradise Creek Formation have average values of 12 ppm (max 28 ppm) Pb and 17 ppm (max 30 ppm) Zn (McGoldrick, 1994).

Evaporites

Most evaporites incorporate extraneous cations of Cu, Pb and Zn during precipitation. For example, sea salt contains 0.8-1.3 mg Pb per kg compared to 3.5-8.0 mg per cubic metre of seawater. Permian Zeichstein evaporites contain 60-560 ppm Pb in halite and 200-1440 ppm in sylvanites (Sonnenfeld, 1984). These metals in evaporites are released during the transformation from gypsum to anhydrite or by dissolution. Migrating basinal brines that dissolve subsurface evaporites can become metal-enriched by this process. Brines derived from the Jurassic Louann salt contain 100 mg/L Pb and 360 mg/L Zn. When these brines cool to 25°C they precipitate native lead (Sonnenfeld, 1984). Brines derived from the dissolution of evaporites are also implicated in Mississippi Valley-type mineralisation (*e.g.* Kharaka *et al.*, 1987 and references therein).

The potential of evaporites as metal sources in the Mount Isa Basin should not be overstated. Although evaporite pseudomorphs are widespread throughout much of the exposed stratigraphy, and fluid inclusion studies (*e.g.* Lisk *et al.*, 1991 and Section 13.4.6) can be interpreted to suggest that basinal brines were derived from evaporites, substantial thicknesses of bedded evaporites are, as yet, unrecognised.

13.4.3 The Origin of the Laminations in Ore

The finely laminated ores in the Lady Loretta, HYC and Mount Isa ore bodies are superficially similar in appearance and consist of thousands of concordant internally-layered bands of mineralisation without any significant contemporaneous cross-cutting relationships. The origin of this lamination remains a point of debate amongst advocates of biogenic, exhalative and replacement mineralising mechanisms. Textural studies of other laminated sulphide ore bodies, including the concept of diagenetic formation, are reviewed below. Although numerous experimental studies have attempted to simulate the laminated ore of the north Australian SSHBM ore bodies, this literature is not commonly cited in economic studies. A summary is presented below.

Textural Studies

There have been few textural studies that specifically address the lamination of sediment-hosted sulphide ore. Amstutz *et al.* (1972) briefly described what they termed "rhythmites" in stratabound ore deposits and Bogush and Savchenko (1971) described rhythmic lamination in the highly pyritic sulphide ores of the Vlasenchikhino deposit, northern Caucasus. Bartholome (1969) drew attention to lamination within the Cu ore of several deposits.

Fontbote (1981) and Fontbote and Amstutz *et al.* (1972) described laminated and thin bedded ores, ore and gangue and shallow marine (tidal, lagoonal and barrier) dolostones from several Spanish, Polish and Peruvian stratabound Zn-Pb(±F-Ba) ore bodies. Fontbote (1981) identified a "type sequence" of banding from these deposits and developed the concept of "diagenetic crystallisation rhythmites (DCRs)" based on the theory of differentiation by crystallisation fractionation. Fontbote (1981) argued that the widespread occurrence of DCRs and their consistent association with specific host facies, indicated that mineralisation was a surface-linked process. He envisaged a two phase process with mineralisation within the first millimetres to decimetres of the sediment. This was followed by a diagenetic crystallisation in a partly closed system. The concept of DCRs was adopted by El Aref (1984) who described laminated Fe sulphides, sulphur, and galena in an evaporitic Miocene sequence from Egypt.

Although Fontbote's work failed to gain widespread acceptance, especially amongst advocates of late-epigenetic MVT mineralisation, it remains as one of the few objective studies of lamination and banding in sediment-hosted Zn-Pb ores. The DCR model certainly has flaws, but it deserves acknowledgment as some current genetic models for HYC and Lady Loretta (see Section 13.5.4) also appeal to mineralisation just below the sediment/water interface, but still rely on simple replacement to explain the lamination of the ore.

Experimental Studies

Numerous studies have been undertaken in attempts to experimentally produce the laminations present in the ore of SSHBM deposits. These studies are reviewed in Bubela (1981a) and Table 13.3. Small-scale experiments by Bubela and McDonald (1969), Lambert and Bubela (1970), Temple and Le Roux (1964) and Weiss and Amstutz (1966) produced banding of varying metal composition from solutions containing Pb, Zn and Cu with, and without, bacterial activity. In several of these studies, the metals did not separate according to their solubilities; Cu was spread thoughout, Pb accumulated in the middle of the zone and Zn travelled furthest before it precipitated. After this initial encouragement, Bubela *et al.* (1975) scaled up to a more realistic kilolitre apparatus with natural brines and both bacteria and algae. Metastable carbonates containing significant enrichment of Pb, Zn, Mn, and Fe were produced but the anticipated monomineralic metal bands did not form. Bubela (1981b) also tested the Williams (1978) model for HYC by experimentally demonstrating that lateral migration of brines produced monomineralic bands that, on a small scale at least, were parallel to the direction of flow. The experimental work culminated when Bubela (1981a) proposed a model for mineralisation based on that of Renfro (1974) (see Section 13.5.3).

13.4.4 Source of Sulphur

Isotopic studies led McGoldrick *et al.* (1995) to conclude that the base metal sulphides and at least some pyrite share a common sulphur source. A direct sulphate source is unlikely; early diagenetic Fe monosulphides or microbial sulphate reduction are the most likely. The former would also liberate Fe which would help stabilise siderite and/or Fe carbonates.

13.4.5 Fluid Source

Fluids that might have been involved in the mineralisation process may have been derived from:

- pore waters liberated during episodic dewatering of basinal shales as advocated by Sawkins (1984) and others
- water generated or exchanged during diagenesis
- metamorphic dehydration reactions (discussed in Russell, 1983)
- surface water (seawater or fresh)
- meteoric water circulation
- magmatic fluids
- the mantle (for those who believe in mantle-tapping faults under Mount Isa)
- various combinations of the above.

Gustafson (1981) and Muir *et al.* (1985) discussed the fluid source responsible for base metal mineralisation in the McArthur Basin and concluded that basin-derived connate and/or surface waters were involved in the genesis of the larger ore bodies.

The source of the fluids that produced the Lady Loretta ore body is the subject of on-going work involving fluid inclusion studies.

Objective	Scale	Fluid	Fluid Flow	Media	Biological Agent	Results	Reference
simulate influx of freshwater with adsorbed metals into saline microbial environment	test-tube	NaCl	repeated additions	agar gel, ground rocks, ferric hydroxide	anaerobic bacteria	Zn→Cu→Fe→Pb (mixing fluids) Cu→Zn→Pb (ferric hydroxide)	Temple & Le Roux (1964)
test if ion exchange on clay can produce metal lamination	test-tube	Na_2S	static	quartz sand	none	Pb-bearing lenses concentric Zn sulphide bands	Weiss & Amstutz (1966)
test diffusion of metal ions ± microbial action	test-tube	Na_2S	static	agar gel, glass beads	± bacteria	bands of varying conc. of Cu, Pb, Zn & metastable Fe sulphides in presence of bacteria	Bubela & McDonald (1969)
produce monomineralic banding in presence of microbes	test-tube	Na_2S	introduced top & bottom	ground rocks	bacteria	formed monomineralic bands Pb→Cu→Zn, galena spheroids and metal carbonates	Lambert & Bubela (1970)
produce monomineralic bands, test role of algae and bacteria, role of metal carbonates	*ca.*1000 L tank	natural brine	static	natural sediments and nesquehonite	bacteria & algae	metastable carbonates containing Pb, Zn, Mn, Fe were ppt, Zn & Pb conc. 200-300 times, Pb in carbonate, Zn in ferric hydroxide, **no** monomineralic layers	Bubela *et al.* (1975) Ferguson *et al.* (1975)
feasibility of lateral migration to produce monomineralic bands	bench-top tank	various soln of Cu/Pb	dual inlets at base	glass beads	none	bands formed parallel to direction of flow	Bubela (1981b)

Table 13.3: Summary of the experimental production of banded sulphides.

13.4.6 Fluid Temperature and Chemistry

Fluid Inclusion Studies

To date, no fluid inclusion data are available from the Lady Loretta ore body, although a pilot study was underway at the time of writing. Such studies from elsewhere in the basin indicate a complex fluid history as would be expected in a polyphase basin.

Petroleum studies of Fickling Group carbonates reported in Lisk *et al.* (1991) found inclusions in quartz overgrowths with 10 to >20 wt% NaCl eq. at equilibrium temperatures of 102°C. The composition of inclusions in late carbonate cements were interpreted to indicate a >20 wt% NaCl eq. fluid at 125-135°C. An immiscible methane phase was present. Burial history modeling suggests that the fluid inclusion temperatures are maximum palaeotemperatures. Diagenetically altered marine or meteoric connate waters or deep basinal brines associated with evaporites are all possible sources, but the latter was considered most likely. Modeling indicates that these brines were theoretically capable of transporting base metals (Lisk *et al.*, 1991).

Fluid inclusions studies from the Zn-Pb-Cu-Ag mineralisation in the overlying Mount Les Siltstone (also Fickling Group) further towards the northern edge of the basin can be interpreted to suggest the involvement of several fluids. Initial metal transport was by 6-7 wt% NaCl fluids at temperatures of 180°C and precipitation was induced by mixing with cooler low-salinity connate or meteoric groundwater. Further sulphide mineralisation was associated with hypersaline $CaCl_2$-$MgCl_2$ brines (up to 30 wt% eq.) at temperatures from 70°C to 125°C (Rohrlach *et al.*, 1996).

Fluid inclusion studies of the mineralisation in the Gunpowder Creek Formation at Kamarga indicate salinities between 16 and 22 wt% NaCl. Temperatures for the various mineral phases range from a minimum of 160°C to a maximum of 355°C (Jones, 1986).

Chemical Modeling

Chemical modeling by Cooke (1993a *et seq.*) indicated that more than one fluid is probably necessary to produce the mineral suite present at Lady Loretta. The interpreted temperatures and compositions of the fluids involved are discussed in McGoldrick *et al.* (1995, 1996*). Metals could be carried by a relatively oxidised, near neutral, saline fluid at about 150°C. A water column of at least 40 m would be needed to suppress boiling of this fluid. The lack of physical evidence of boiling, given the shallow sedimentary setting proposed in this study, implies that mineralisation occurred in the subsurface. However, the same fluid cannot carry much (or any) Ba, Mn or Fe so an earlier more reduced hydrothermal fluid is required.

The low Au tenor of the Lady Loretta mineralisation provides indirect evidence of fluid temperature. Ore fluids with the salinities required for adequate Zn and Pb transport must be relatively cool (<200°C) or they would carry significant Au (McGoldrick *et al.*, 1995).

Isotopic Studies

The petroleum studies of the fluid inclusions in the Fickling Group carbonates found oxygen isotope values that correspond to a corrected pore water value of 2.2-3.2‰ $\delta^{18}O_{smow}$ at 140°C. This was not considered diagnostic of a unique derivation (Lisk *et al.*, 1991).

Carr (1981) used the sulphur isotopes of individual sphalerite-galena pairs to calculate a range of equilibrium brine temperatures from 150° to 320°C for the mineralisation at Lady Loretta.

Modeling of the $\delta^{18}O$ data from carbonates in the halo around the Lady Loretta mineralisation indicates that dolomite formed from a 50°C fluid of either meteoric or evaporated seawater origin (Large *et al.*, 1995). The siderite and ankerite could both have formed from a single fluid at about 100°C (Large *et al.*, 1995). Siderite could not have precipitated from the same fluid that formed the dolomite.

13.4.7 Physical Movement of the Fluids

The plumbing system responsible for SSHBM mineralisation is one of the most poorly understood aspects of all genetic models. Not even the syngenetic models have adequately addressed the problems of maintaining through-flow sufficient to deposit the tonnages of metals present in SSHBM deposits. Theories range from mantle-tapping faults to petroleum-style lateral migration of basinal brines.

Identification of the conduits for the mineralising fluids responsible for the Lady Loretta ore body is equally contentious because this study has rejected the Carlton Fault Zone as a likely feeder. On a smaller scale, the prevalence of fluidisation-brecciation and fluid injection or fluid escape features in cores from the mine sequence was first noted and illustrated by McGoldrick (1993) and McGoldrick *et al.* (1995). The present study identified similar features in both synclines and in cores from the Tom Cat area (drillhole LA64 in particular). The correlation presented in Section 10.3.4 indicates that these features occur at similar stratigraphic levels within the Cyclic Unit as well as in the Ore Sequence and Ore Sequence Equivalent. Whether these fluidisation features are related to mineralisation is a moot point, but they certainly indicate the vertical escape of fluid under pressure into unconsolidated sediment from a number of distinct stratigraphic levels.

Another possibility for the fluid conduit at Lady Loretta is the pyritic zone immediately underlying the Ore Sequence. The presence of vuggy porosity in pyrite beds and the unusual reactive pyrite in this zone warrant further investigation.

Fluid Drive

Fluids move in the subsurface under the influence of the following driving forces: gravitational/hydrostatic; thermal; tectonic and chemical. The latter includes osmotic and ion-exchange affects that are commonly overlooked but may be locally significant for the concentration of metals in shales. Regional fluid drive is produced by the interplay of buoyancy, hydrodynamic movement and capillary mechanisms. These mechanisms can produce either episodic or continuous fluid movement (Bethke, 1990).

There are several schools of thought concerning the regional fluid drive and circulation believed responsible for SSHBM mineralisation. The following discussion compares and contrasts models based on long-distance lateral migration, local migration along faults and fractures by hydraulic pumping and a deep-seated convective cell.

Long-Distance Lateral Migration - the Petroleum Migration Model

Broadbent *et al.* (1996), McConachie (1993b) and McConachie and Dunster (1996)* have suggested that the movement of mineralising fluids in the Mount Isa Basin is analogous to petroleum migration; following the same hydrodynamic laws; and that the same, or similar, basin-derived brines may be involved. Such an explanation has long been advocated for MVT mineralisation. However, it comes with several important caveats:

- multiple pulses of brine, or some local focusing mechanism, may be necessary to account for the volume of metals deposited in large SSHBM deposits
- the density dynamic of metal-bearing brines will be different from petroleum and, in the case of the more-dense brines, a base seal may be important
- hydrocarbons are trapped structurally or stratigraphically and although significant volumes remain behind in the conduit (*i.e.* irreducible oil saturation) they do not impede the overall migration; metals on the other hand will be precipitated where-ever conditions are favourable (*e.g.* contact with an organic shale lens in the aquifer) and such deposition will restrict further brine migration
- whereas petroleum migration into a trap is simply a case of filling to spill point, the deposition of metals will require a large volume of through-flow because of constraints imposed by metal solubilities. It is worth noting, however, that oxidised brines can transport a relatively large concentration of metal and thereby potentially reduce the volume of fluid required (McGoldrick *et al.*, 1995).

The last two points are critical and must be considered in any epigenetic model.

Hydrothermal Convection

Hydrothermal convection driven by a granite as a thermal and/or radiogenic heat source has been advocated by several workers (*e.g.* Russell, 1983 and Solomon and Heinrich, 1992; Solomon and Groves, 1994). McNaughton *et al.* (1993) demonstrated that a granite could maintain >200°C for 10^9 years given sufficiently high radiogenic activity and sufficient thermal blanketing. However, the concept of circulation cells as advocated in this model is almost certainly overly simplistic. Basins contain innumerable vertically stacked beds with varying porosity and permeability, density and thermal conductivity. Any number of aquifers could be operating to carry fluids laterally. This fundamental anisotropy is not addressed by the simple vertical convection models as proposed by Russell (1983), Solomon and Heinrich (1992) and Solomon and Groves (1994).

Seismic Pumping and Hydraulic Jacking

Seismic pumping has been invoked to explain mineralisation at HYC (Large *et al.*, 1996) and Mount Isa (Muir, 1981). This mechanism is based on stresses and fluid pressures building up until a critical point when a fracture opens and a pulse of brine is released. The fracture re-seals and pressures again build until the next explusion. Pulsing fluid flow has also been linked to the lamination in MVT ore bodies and has been demonstrated to be associated with active wrench faults (Russell, 1983).

The process of seismic pumping may also open bedding-parallel conduits by the hydraulic jacking along bedding planes. Broadbent *et al.* (1996) advocated this mechanism for late epigenetic mineralisation at Century.

13.4.8 Source of the Iron

Prior to the work of McGoldrick et al. (1995), most workers (*e.g.* Amade, 1986) had interpreted the thousands of beds of pyrite in the vicinity of the Lady Loretta ore body as a product of the mineralising fluids. A conservative estimate is that there are 50 Mt of pyrite associated with the 8.3 Mt Zn-Pb-Ag orebody at Lady Loretta. To bring in this much Fe, fluids would have to be very acid. However, there are still carbonates in the mine stratigraphy, so the logical conclusion is that the Fe existed prior to mineralisation. Syngenetic and early epigenetic pyrite as proposed by McGoldrick et al. (1995, 1996) is the most plausible explanation.

13.4.9 Origin of the Barite Chert

The barite in the vicinity of Lady Loretta mine is the only known example of bedded barite associated with a north Australian SSHBM ore body. The Grevillea prospect contains barite but it is volumetrically less significant and not known to be bedded.

Analyses by Carr (1981) show that the barite at Lady Loretta is relatively pure with some Sr concentrations tending toward celestite. However, the barite is intimately associated with subordinate chert. As shown on the palinspastic reconstructions (Figure 10-4), the barite chert in the Ore Sequence at the Lady Loretta mine is concentrated at the same stratigraphic level on the limbs of both synclines, with sporadic pods distributed across the keels of the synclines. It can be traced, almost continuously, over most of the exposed eastern limb of the Small Syncline. The northwestern limit of the barite chert is unknown because it is truncated by the Carlton Fault Zone, but the remaining barite forms a distinct rim, making the barite chert a facies variant of the ore and the equivalent host rocks. Much of the barite has been recrystallised and/or deformed plastically, but some relict bedding up to about 0.5 m thick and possible primary crystal fabrics from the least deformed zones were described by Aheimer (1994). The nodular-mosaic and mosaic textures that underlie the microbial fabrics on the eastern limb of the Small Syncline are similar to chicken-wire anhydrite from modern sabkha settings (see Section 10.1.11). Elsewhere, barite occurs between the columns of digitate microbialites (Dunster, 1996)*. Aheimer (1994) found that the barite between columnar microbialites contains minor inclusions of anhydrite. The inclusions range from 2.5 μm to 70 μm in diameter and occur in a pseudohexagonal habit and as smaller corroded crystals. Whereas some of the larger anhydrite inclusions transgress barite crystal boundaries (Aheimer, 1994); other smaller anhydrite inclusions are wholly within barite crystals (personal observation).

The previously proposed origins for the barite and its present distribution in the vicinity of the mine include:

- the product of Ba-rich brines exhaling onto the seafloor (Eugster, 1987)

- the result of "the rapid mixing of reduced ore fluids with more oxidised basin waters" with the barite restricted to a small area marginal to a topographic depression (Large, 1980; Carr, 1981)
- the product of "mixing of Ba-rich hydrothermal fluids with seawater sulphate (?brine pools) in either a distal or lower temperature setting relative to that for Pb deposition" (Derrick, 1993)
- precipitation at the interface of anoxic and oxygenated sediments analogous to Lake Malawi (Robbins, 1983)
- a low temperature precipitate resulting from the bacterial breakdown of thiosulphate from the metal-bearing brine in the presence of organic matter (an analogy to MVT-mineralisation drawn by Spirakis and Heyl (1993))
- the product of an earlier lower temperature (or less evolved) hydrothermal fluid than carried the metals, with the barite accumulating as a 'bath-tub ring' where the redoxcline intersected the sediment/water interface (see McGoldrick *et al.*, 1996)*
- a replacement of original sulphate evaporite (on the basis of evidence presented in Dunster, 1996*; the anhydrite inclusions described above and analogy with commercial quantities of barite that pseudomorph evaporitic gypsum in the Archaean of W.A.)
- an alteration product of the mineralisation (Grant, pers. comm., 1997)
- a structural remobilisation of pre-existing barite onto the limbs of the syncline as suggested by Keele (pers. comm., 1995; which does not answer the question of the source).

As several of these scenarios have been discussed at length elsewhere, the following discussion concentrates on the possibility of a hydrothermal source and discusses the ultimate source of the Ba.

Eugster (1987) considered the presence of barite at Lady Loretta mine directly comparable to Meggen and Rammelsberg in Germany and Silvermines and Tom on the Irish Shelf. He made the analogy with deposits associated with white smokers since such chimneys contain amorphous silica and barite. Anhydrite, gypsum and barite form when hot Na-Ca-Cl geothermal fluids come in contact with seawater. After cooling, anhydrite and gypsum dissolve. Barite is much less soluble and accumulates in substantial amounts in the oxidised part of the basin. Thus, Eugster (1987) concluded that the presence of bedded barite at Lady Loretta mine indicated that deposition occurred in the presence of seawater and that hot fluids rich in Ca and Ba were responsible for the mineralisation (Eugster, 1987). Similar exhalative models proposed by Large (1980) and Carr (1981) imply that the same hydrothermal fluid carried both barite and the metals. However, chemical modeling by Cooke (1994), can be interpreted to indicate that the relatively cool highly oxidised fluids implicated for base metal mineralisation were unlikely to also carry significant quantities of barite.

The relatively high $\delta^{34}S$ (+37.4 to +39.7%) of the barite could be explained by brines becoming enriched in the heavy isotope after deposition of the pyrite and ore (Carr, 1981).

Solomon and Groves (1994) suggested "partial reduction of marine sulphate during deep-seated fluid circulation".

Few workers have considered the ultimate source of the Ba. The average Ba content of present seawater is only 5 ppb and freshwater 54 ppb (Bolze *et al.*, 1974). If values were similar during the Proterozoic, this would rule out primary chemical precipitation from typical surface waters. Barite carried by hydrothermal fluids may have been derived from the solution of evaporites in the basin or stripped from sedimentary or volcanic rocks. The metabasalts in the Eastern Creek Volcanics, with up to 600 ppm Ba, are a potential source. However, since these rocks are thought by some workers to have also been the source of the Cu-Zn-Pb-Ag (see Section 13.4.2) geochemical modeling would need to demonstrate that it is possible to simultaneously strip metals and Ba.

13.4.10 The "Trap"

The concept of a "trap" has gained acceptance as petroleum terminology is being used increasingly in metal exploration. Organic-rich sediments are almost unanimously cited as the reductant responsible for the deposition of metals. Another possibility is reservoired hydrocarbons. If that were the case, the petroleum model might be taken further to argue for stratigraphic and/or structural control and the implicit presence of a seal. However, this would have to be argued separately for the migration of petroleum and the mineralising fluids, since the timing of the two events might have been quite different.

13.5 REVIEW OF POSSIBLE MODELS

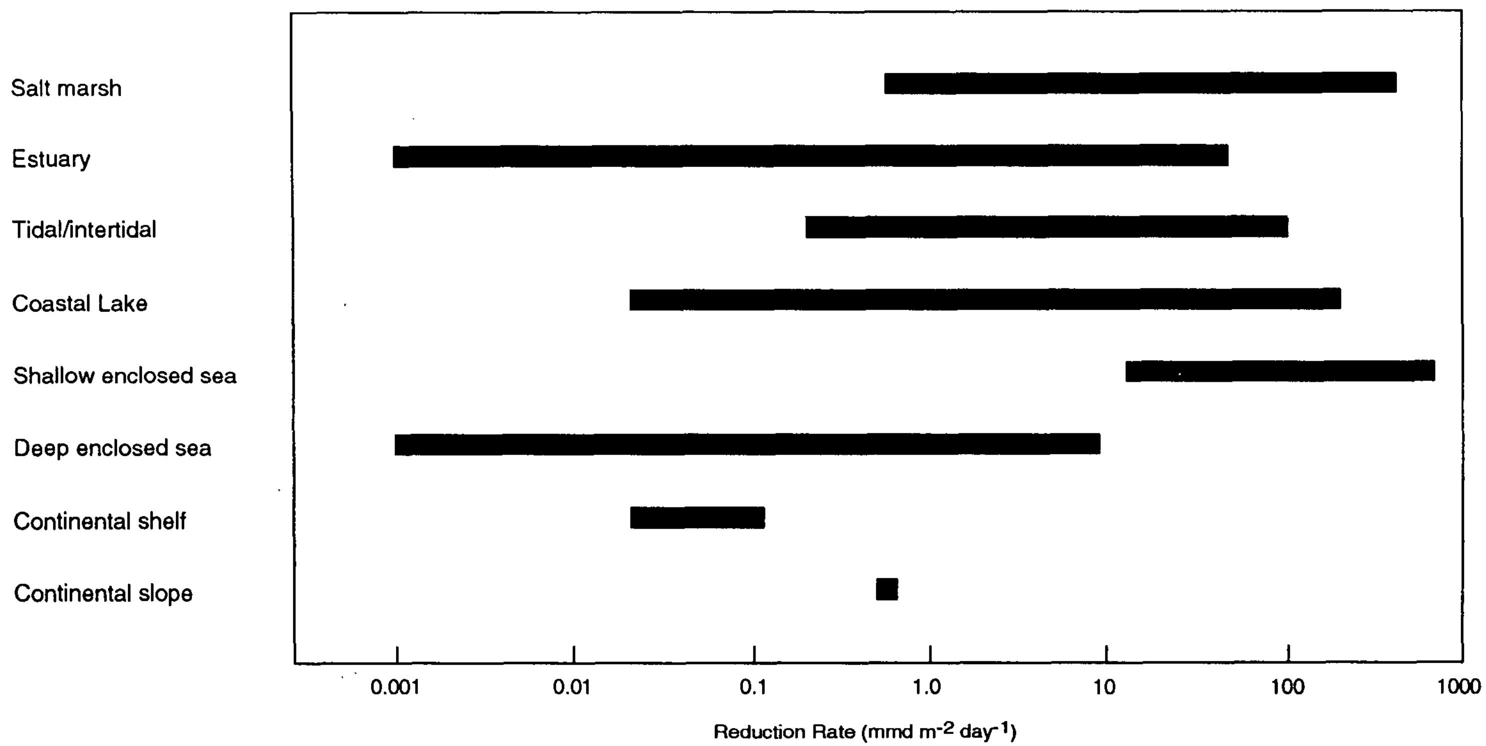
13.5.1 Syngenetic - Bioaccumulation

Many authors have noted the high organic carbon component associated with SSHBM ore bodies and interpreted this as evidence of prolific microbial activity. This is supported by the presence of microbialites at Lady Loretta and the locally abundant microfossils at HYC and other ore bodies, as discussed at length by Brongersma-Sanders (1992). Some workers (*e.g.* Baas Becking, 1925; Sonnenfeld *et al.*, 1977; Taher *et al.*, 1994) studied modern sulphate-reducing bacteria and then argued that microbial activity could be responsible for the direct precipitation of significant quantities of metal sulphide ores from the ambient water column. Analogies can be drawn with the large quantities of pyrite associated with some SSHBM ore bodies that some authors suggested are of biological origin (*e.g.* Eldridge *et al.*, 1988), with BIFs that were thought to be microbially precipitated and with microbialites that extracted and precipitated thousands of tons of carbonate from seawater to produce Proterozoic reefs. Several laboratory studies attempting to biologically precipitate metal sulphides have been carried out (see Section 13.4.3). However, base metal accumulation by sulphate-reducing bacteria would require water significantly more enriched in metals and sulphate than present seawater and/or much more effective microbes. Whereas some extant bacteria, such as some species of *Desulfovibrio* and *Thiobacillus*, can concentrate significant amounts of metal (in the latter case, >25% Ag_2S

per gram of dry weight - Pooley, 1982), they have to be growing in a metal-rich environment to begin with.

Modern sulphate-reducing bacteria are a diverse group, sometimes living in syntropic growth mixtures, and individual species have been cultured from Antarctic waters close to 0°C and hydrothermal springs in excess of 80°C. They are also known from a wide range of salinities and pH conditions, ranging from alkaline lakes (pH 10) to acid mine drainage with a pH of 2-5 (Trudinger, 1992). The sulphate reduction rates in salt marshes, coastal lakes and shallow enclosed marine bodies are significantly greater than anoxic deep sea environments (Figure 13-4). Field studies of modern hypersaline microbial mat found that metals, including Pb, Cu and Fe, were concentrated 2-3 times above equivalent sediments lacking microbial mat (Taher *et al.*, 1994). The absolute concentrations recorded are summarised in Table 13.4.

Figure 13-4: A comparison of the sulphate reduction rates in a variety of sedimentary environments.


Salt marsh
Estuary
Tidal/intertidal
Coastal Lake
Shallow enclosed sea
Deep enclosed sea
Continental shelf
Continental slope
0.001
0.01
0.1
1.0
10
100
1000
Reduction Rate (mmd m-2 day-1)

Metal	Lacking Microbial Mat		With Microbial Mat	
	μ	Range	μ	Range
Fe	2202	1201-2700	5711	3219-9200
Co	1.48	0.57-2.33	4.04	3.12-4.89
Pb	1.16	0.78-2.05	3.27	2.00-5.55
Cu	3.00	1.01-4.62	7.90	5.62-11.43
Ni	< 1.0	< 1.0	< 5.0	<5.0
Cr	0	0	Tr	Tr

Table 13.4: Metal concentrations in modern Port Said salina sediments from Taher et al. (1994). The results are in μg/g (≅ ppm).

These authors concluded that "recent hypersaline environments with ambient microbial mat ... are ideal examples of present-day environments of metal accumulation". However, given the low absolute concentrations reported and even allowing for dewatering and compaction, it could hardly be argued that an ore body would result directly from microbial activity. The resultant sedimentary rocks could however, be a source of metals comparable to many volcanic rocks.

Significantly higher concentrations of metals were found in organic matter accumulating at the bottom of a thermally stratified microbial lagoon. The sediments contained a high proportion of microbially-derived organic material and were enriched in Cu, Pb, Mn, Fe and Zn relative to the water and to adjacent sediments. The last three elements were approaching, or exceeded, percent level (Sonnenfeld *et al.*, 1977; see discussion of Lago Pueblo in Section 10.1.8). Indeed, averaged over a ten metre stratigraphic interval, the concentrations of Zn and Mn were higher than those reported from the Atlantis II Deep in the Red Sea (Durga Prasada Rao *et al.*, 1984) that is commonly cited as a modern analogue of base metal mineralisation.

Calculations based on the present rate of biological sulphate reduction indicate that a sediment covered by a static 21 m column of 0.2 mM (*i.e.* 13 ppm Zn) metal solution and supporting a typical sulphate reduction rate of 20 mM m^{-2} day^{-1} could be covered by a 100 μm thick layer of ZnS in 212 days *i.e.* it would take 58 years to accumulate 1 cm thickness. If the same solution flowed at a rate of only 1.0 cm day^{-1} over a sediment surface area of 1 m^2, 1 cm of ore could be deposited in 5.8 years and 21 000 L of the solution would be required (Skyring, 1981).

Whether these sulphides would be preserved is another issue. Even ignoring the influx of detrital material and the inevitable disruptions to sedimentation by storms *etc.*, chemical and biological processes also mitigate against long-term preservation. Observations of pyrite formation at Solar Lake show that while biologically-mediated production of pyrite can be very high (*e.g.* 800 g S m^{-2} $year^{-1}$) less than 0.1% remains fixed as metal sulphides, the remainder reverting to sulphate. This has lead many workers (*e.g.*

Trudinger, 1981) to advocate a mixed biogenic/hydrothermal source for pyrite. Lake Kivu in the East Africa rift valley and the Guaymas Basin are cited as possible examples.

Experimental work that attempted to simulate the lamination of SSHBM ore bodies by bacterial precipitation at surface conditions found that much of the metal was being deposited as metastable carbonates (Lambert and Bublea, 1970; Bubela *et al.*, 1975). Since the metals were already in the system at the time of precipitation and could be converted to sulphides shortly after burial, this a true diagenetic model (*sensu* Tourtlet and Vine, 1976). Such a model may warrant more attention, given the debate about the potential for unusual carbonate chemistry at various times during the Proterozoic as reflected by the precipitation of primary dolomite, aragonite or calcite.

Microbial activity can result in other processes that may have some bearing on mineralisation but are not normally considered in purely chemical studies. For instance, bacteria can precipitate Fe^{2+} and Fe^{3+} simultaneously in close proximity. Aerobic forms precipitate protoferrihydrite ($\rightarrow$haematite) and aerobic activity in the same microbial community results in siderite (Sawicki *et al.*, 1995). Anaerobic bacteria are also capable of mobilising Ba from barite by sulphate reduction at surface conditions (Bolze *et al.*, 1974). This is in marked contrast to the chemical insolubility of barite under the same conditions.

Most economic geologists have not seriously considered syngenetic bio-accumulation as a viable mechanism for mineralisation in any north Australian SSHBM ore body. However, Trudinger (1992) advocated such a mechanism for HYC, Mount Isa and some Cu deposits in the Kupferscheifer. Webster (1996) suggested it for Broken Hill. Biological precipitation would explain the lamination of the ore and is consistent with the presence of microbialites in the host rocks at Lady Loretta. However, proving this mechanism would be difficult. To use this model predictively would require biological, sedimentological and palaeogeographic control beyond the present level of understanding for the Proterozoic of northern Australia.

13.5.2 Syngenetic - Exhalative

Most textbooks (*e.g.* Edwards and Atkinson 1986; Legge and Lambert, 1994) propose the classic SEDEX model, in which metal-bearing brines exhale onto the seafloor, for all the north Australian SSHBM ore bodies. Currently, it is the most commonly cited model for the HYC ore body (R. R. Large *et al.*, 1996; but *cf.* Hinman, 1996) and the Walford Creek prospect (Rohrlach *et al.*, 1996).

A syngenetic exhalative model for the Lady Loretta ore was first proposed during the mid 1970s (Loudon *et al.*, 1975; Cavaney 1975). At that time, Red Sea exhalative models were in vogue and many workers also advocated such a model for the Mount Isa ore. D. E. Large's (1980) seminal paper on submarine exhalative Pb-Zn ore bodies cited Lady Loretta as an example and this influenced much of the later work, including Eugster (1987) who thought it typified marine SEDEX deposits based on the presence of barite.

Carr (1981) recognised that the bedded cherts at Lady Loretta were not exhalites and challenged several of the other criteria used by Large (1980). Table 13.5 summarises the present understanding of the Lady Loretta ore body in relation to the submarine exhalative criteria used by Large (1980). It is obvious that his original deep water SEDEX model is no longer likely. In particular, this study was instrumental in challenging the syn-sedimentary graben and deep water setting.

CRITERIA FROM D. E. LARGE (1980)	LADY LORETTA EXAMPLE	CURRENT INTERPRETATION
fault bounded graben or half graben as first order basin	syn-sedimentary Paradise Graben	no evidence of local graben
syndepositional fault activity	Carlton Fault Zone	no evidence
evidence for syntectonic activity	turbidites in footwall and hanging wall, slumps and breccias in ore horizon	turbidite model contested, few sedimentary slumps in ore, breccias are minor and also occur away from the mine and faults
contemporaneous igneous activity	tuffs	many "tuffs" may not have had any volcanic component, true tuffs not restricted to time of mineralisation
evidence of a third order basin	synformal structure	folding was post mineralisation
euxinic environment in restricted basin	low energy sediments, high C black shales in ore sediments, deep water sediments	shallower water setting now proposed
diagenetic pyrite becomes isotopically heavier up section	Carr & Smith (1984)	evidence of restricted circulation, small volume of water
presence of stratiform exhalative barite	low Sr content, narrow range of $\delta^{34}S$	barite contains microbial fabrics, $\delta^{34}S$ may reflect impounded water
stratiform hydrothermal chert	large volume, restricted to host sediments	not restricted to host sediments, pseudomorphs microbial and possible evaporite textures

Table 13.5: Reinterpretation of the criteria originally used by D. E. Large (1980) to argue for a syngenetic origin of the Lady Loretta ore.

Several companies used syngenetic models based on Large (1980) and located similar host rocks to the Lady Loretta ore body at other locations in the Lady Loretta Formation (see Section 14.2).

13.5.3 Early Epigenetic - The Renfro/Garlick Sabkha Model

In 1974, Renfro published a controversial model for the genesis of stratiform sediment-hosted Cu±(Pb-Zn) ore bodies. The model proposed:

- a sabkha-supratidal site of mineralisation
- vertical flow of the metal-bearing brines through the zone of sulphide mineralisation
- buried bacterial mats as the substrate for bacterial sulphate reduction.

This model was modified by Bubela (1981a) and Garlick (1981) who proposed:

- an intertidal/subtidal site of mineralisation
- lateral flow and discharge of metal-bearing brines
- surface or near-surface *in situ* or detrital bacterial substrates for sulphate reduction.

Since Bubela (1981a) proposed that the bulk of mineralisation was in the shallow subsurface, this is considered an early epigenetic model. However, the same mechanism discharging mineralising fluids at the sediment/water interface is strictly syngenetic.

A similar model was used by Eugster (1985) to explain the HYC SSHBM mineralisation and the Cu-Co ores of southeast Finland. Eugster (1987), however, regarded the Lady Loretta mineralisation as classic marine SEDEX (see previous Section). The original Renfro/ Garlick model was discussed by Warren (1997). The model was further developed by Ferguson and Skyring (1995) who invoked a marine sabkha similar to Nilemah Embayment in Shark Bay as an analogue. In their model, a highly porous and permeable aquifer in a redbed package on a continental coastal plain extends seaward to discharge into topographic depressions on the carbonate tidal flat. Metals are derived from volcanics or sedimentary rocks in the hinterland and carried through the oxidised aquifer into reducing, organic-rich, intertidal sites of metal deposition. The metal-bearing brines are concentrated by a process of repeated discharge into playas allowing evaporitic concentration before refluxing and continuing down the gradient to the sea.

Studies of the modern clastic sabkha adjacent to Laguna Madre did not confirm the hydrodynamic model proposed by Renfro (1974) for metal concentration, but identified algal mats as a sink for trace-metal accumulation (Long, 1983). Long *et al.* (1985) studied several hydraulically different modern marine sabkhat and found no elevation of trace-metal concentration compared to the adjacent near-shore marine sediments.

However, other redbed sequences are known to contain metal rich brines. A 2800 m sequence of Neogene redbeds on the Cheleken Peninsula of the Caspian Sea has a normal geothermal gradient and there is no known igneous activity. Sodium chloride brines recovered during hydrocarbon production range from 150 to 290 g/L NaCl and contain 0.2-5.4 ppm Zn and 2-77 ppm Pb. The brines are believed to be derived from evaporites and the Pb is believed to be transported as $PbCl_4^{2-}$ (Sonnenfeld, 1984). Despite a bottom hole temperature of only 80°C, these brines precipitate abundant sphalerite, galena and pyrite on well casing and surface tanks. Growth rates of these sulphide precipitates can be quite rapid: a 2.5 mm crust of sphalerite was observed to form in three months (Lebedev, 1972).

The Ferguson and Skyring (1995) model could be applied to the Lady Loretta ore body. If the palaeogeography proposed by Hutton and Sweet (1982) and supported by this study (see Section 10.5) is accepted, a mountain range was present a few tens of kilometres to the west of the present orebody. A substantial thickness of redbeds and pseudomorphs of bedded evaporite occur in the Trent section between the mountains and the nearest reduced marine sediments in the vicinity of the present mine. The discharge of metal-bearing brines into a shallow lagoon is also consistent with the Renfro/Garlick model. Although this model has not previously been considered for the Lady Loretta ore body, it has some elements in common with that proposed by Harris (1984, 1993). In particular, it could be used to explain both the Zn-Pb-Ag mineralisation at Lady Loretta and (possibly early) Cu mineralisation in older rocks just to the northwest of Lady Loretta.

This model could be used predictively by identifying the redbed to marine transition in any one of several potentially suitable formations in the Mount Isa and McArthur Basins.

13.5.4 Early Epigenetic - The Martin *et al.* Lagoonal Model

Fontbote (1981) and Martin *et al.* (1987) proposed a mineralisation model for the F-Pb-Zn ore bodies in the Triassic of Spain. They envisaged the sedimentary environment of the host rocks as "highly restricted lagoons isolated from the open sea by calcarenitic barriers with noticeable development of algal mats in their inner margins." Fluorite and base metals were interpreted to have formed "under surface-linked conditions ... in a way similar to that of early-diagenetic dolomite." However, most workers would now regard the textures they illustrated as typical of late epigenetic MVT ore bodies.

13.5.5 Early Epigenetic - The McGoldrick *et al.* Lagoonal Model

The most recently proposed model for the genesis of the Lady Loretta ore body is that of McGoldrick *et al.* (1995, 1996*). This model is based on extensive geochemical data and stresses the role of precursor host sediments. Mineralisation is believed to have been both syngenetic at the sediment/water interface and as subsurface infillings and possible replacement of unlithified sediments. As such, the current study considers the model to be early epigenetic. A four stage process is envisioned, in which ore minerals were precipitated during Stage 3. The following precis is paraphrased from McGoldrick *et al.* (1996* - see Appendix A-14).

Stage 1

Deposition of the upper most Carbonate Unit and the Pyritic Unit was accompanied by the growth of subordinate benthic microbial mats and/or a rain of detrital organic matter. The carbonates were in equilibrium with water containing isotopically light oxygen.

Stage 2

Low temperature (<100°C) moderately oxidised (pyrite stable - near haematite boundary) groundwaters moved laterally and vertically through the unconsolidated sediments and escaped to the overlying water column. The migrating fluid had a distinctly heavier oxygen isotope signature than the connate pore waters that it displaced. The discharging fluid supplied energy, nutrients, Fe and some Ba to the ambient sedimentary environment, stimulating proliferation of microbial activity. Barite was precipitated when the fluid mixed with oxygenated bottom waters and/or the fluid reacted with sulphate evaporite minerals in the sediment pile. Decomposition of microbial remains in the sediment subsurface, accompanied by biogenic sulphate reduction produced reduced sulphur (and CO_2) which reacted with the Fe to form Fe sulphides. Acidity produced during Fe sulphide precipitation promoted dissolution of detrital carbonate and oxyhydroxides that were locally reprecipitated as ferroan carbonates (ankerite and some siderite). Circulation in the overlying water body became restricted at about this time. Bottom waters were periodically anoxic and contained free H_2S. Living digitate and prone microbialites were restricted to the oxygenated fringes of the "hydrothermal oasis" (the author prefers "putrid bog") that was probably <1 km across on the margin of the larger lagoon. A pelagic rain of abundant organic matter continued throughout the lagoon. Barite accumulated as a "bath-tub" ring where the redoxcline intersected the basin floor.

Stage 3

The groundwaters being discharged evolved to become more oxidised (haematite stable) and may have been slightly warmer (100-120°C). These fluids retained the oxygen isotope signature of their more reduced precursor and carried significant concentrations of Zn and Pb, but much less Fe and Ba than previously. Base metal sulphides precipitated when this evolved fluid encountered pore waters and bottom waters containing reduced sulphur species. Reactive diagenetic Fe monosulphides may have also provided reduced sulphur. Iron liberated by this process was incorporated into Fe carbonates or recycled into new Fe sulphides. Some metal sulphides accumulated as syngenetic beds on the lagoon floor, but considerable quantities were probably precipitated in the shallow subsurface anoxic sediments. The Cu- and Pb-rich parts of the ore formed where the reduced sulphur supply was limited (*e.g.* parts of the sequence with a greater clastic sedimentary component). Acidity generated during metal sulphide precipitation promoted dissolution of detrital carbonate, earlier carbonate cements and any remaining Fe monosulphides. Siderite may have been precipitated locally. The lower pH helped to stabilise marcasite and may have promoted some silica deposition. Excess Zn was incorporated into siderite where reduced sulphur was the limiting factor in metal sulphide precipitation and/or in areas with very high effective PCO_2. Minor traces of haematite in the mineralisation may be an alteration effect of the oxidised base metal bearing fluid.

Stage 2 and 3 conditions probably fluctuated over the time interval represented by the 20 to 40 m thick mineralised sequence and were probably more laterally extensive than Stage 3.

Stage 4

Barite deposition had ceased but the persistence of large amounts of syndiagenetic pyrite and associated geochemical anomalies for more than 100 m into the Cyclic Unit can be interpreted to indicate that the mineralising system waned slowly.

Discussion

Several aspects of this model are similar to that recently proposed for the HYC ore body by Hinman (1996). Both models advocate mineralisation 10-20 m below the sediment/water interface by a laterally-discharging dense brine with some vertical leakage. The conduit was interpreted as zones of permeability and porosity in differentially consolidating, cyclically-interbedded silty to muddy sediments (Hinman, 1996).

The McGoldrick *et al.* (1996)* lagoonal model is predictive by using sedimentological and sequence stratigraphic studies to identify suitable lagoonal host rocks. An additional component to this model is the use of geochemical vectors derived from studies of the halo around the Lady Loretta ore body (see Section 14.4.2).

13.5.6 Late Epigenetic - Basin Compaction Model

Petroleum-style models that invoke long distance lateral migration of brines and deposition of metals in stratigraphic or structural traps have been proposed for Mississippi Valley-type mineralisation. Such models for base metal mineralisation in the north Australian zinc belt were advocated by McConachie (1993b) and McConachie and Dunster (1996)* who argued that dolomitisation, palaeo-thermal anomalies and epigenetic mineralisation were produced by basinal brines migrating through lowstand system tract aquifers and along sequence boundaries overlying fine-grained highstand systems tracts that act as basal seals (see McConachie and Dunster, 1996)*.

A similar epigenetic model has been proposed for the Century SSHBM ore body (Broadbent *et al.*, 1996) in which deep basin brines generated during basin inversion and regional deformation were focused along faults. A hot metal-bearing hydrothermal fluid caused the rapid maturation of organic material in shales, generated oil and gas, and ultimately led to sulphate reduction and base metal precipitation. The hydrocarbons were reservoired in an overpressured zone and the area of most intense mineralisation is interpreted as the palaeo- oil/gas contact (Broadbent *et al.*, 1996).

The proposition that SSHBM mineralisation is produced by basinal brines is usually counted by arguing that such brines could not have attained (or retained) a sufficiently high temperature (see discussions in Edwards and Atkinson, 1986; Russell, 1983; Solomon and Heinrich, 1992). However, these authors may have underestimated the thickness of the basin and the potential temperatures of the fluids generated. They may have also overestimated the fluid temperatures necessary to carry metals (see Section 13.4.6).

Russell (1983) also criticised this model by arguing that SSHBM deposits should be clustered around the basin margin like Mississippi Valley-type ore bodies. This merely reflects the relative timing of fluid migration and the style of deformation in the archetypical Mississippi Valley terrain. By analogy with petroleum migration and MVT deposits in the Canning Basin (for example), the basin edge theory is overly simplistic and should not be applied universally.

McConachie and Dunster (1996)* suggested that a petroleum-style late-epigenetic mineralisation model could be used predictively in the Bowthorn Block of the northern Mount Isa Basin where there is seismic coverage. It may be possible to extend this methodology into other areas by using the sequence stratigraphic approach advocated by NABRE (Southgate *et al.*, 1996).

13.5.7 Late Epigenetic - Syn-Deformation or Syn-Peak Metamorphism

There are numerous advocates of late epigenetic syn-tectonic and syn-metamorphic replacement models for SSHBM ore bodies. In particular, this has remained a favoured model for the Mount Isa ore bodies for several decades although there is still considerable debate on the details, even amongst proponents (*e.g.* Bell and Hickey, 1996; Perkins, 1984 *et seq.*; Lister *et al.*, 1996; Myers *et al.*, 1996).

Carr (1981) discussed several late epigenetic theories for the origin of the Lady Loretta mineralisation. Since there is no evidence that the mineralisation is filling existing porosity in the host rocks, epigenetic mineralisation must have been replacive. He could find no textural evidence that mineralisation was replacing pyrite (although Aheimer (1994) did, at least on a small scale). Carr (1981) considered interbedded siderite and highly carbonaceous matter the most likely to have been replaced by mineralisation.

The timing of epigenetic mineralisation at Lady Loretta is unlikely to be the same as advocated at Mount Isa. The Zn-Pb-Ag mineralisation (and some would argue, the Cu) at Mount Isa has been related to the D2 or D2.5 phase of the Isan orogeny (Perkins, 1990; Bell and Hickey, 1996). What is believed to be the same folding event has clearly deformed, remobilised and recrystallised much of the sulphide and sulphate mineralisation at Lady Loretta (McGoldrick *et al.*, 1995).

One of the major problems with any late replacement model for SSHBM ore bodies in general, and Lady Loretta in particular, is the formation of literally thousands of concordant internally-layered bands of mineralisation without any significant cross-cutting relationships. This is difficult to explain in what should have been consolidated argillaceous rocks with little remnant porosity and permeability.

An attraction of this model is that it can be used predictively by locating tectonic structures of the appropriate generation and containing suitable host facies.

13.6 SUMMARY

All of the models discussed above have their strengths and weaknesses and most can be used predictively. Whereas other north Australian SSHBM ore bodies have similar ages of the host sediments and mineralisation, Lady Loretta apparently does not. Thus, if the dating is correct, the syngenetic and early epigenetic models are flawed. However, late epigenetic models must invoke replacement for which there is little textural evidence, explain the fine lamination evident in the ore and the absence of contemporaneous cross-cutting relationships.

Chapter 14 - Towards an Exploration Model

14. TOWARDS AN EXPLORATION MODEL FOR SSHBM ORE BODIES

14.1 EXPLORATION IN THE NORTHERN AUSTRALIAN ZINC BELT - HISTORICAL PERSPECTIVE

The Dugald River Zn-Pb ore body was probably the first significant sediment-hosted ore body discovered in the north Australian zinc belt. Discovery of the gossan pre-dates R. L. Jack's visit in 1881 as he noted the presence of pits and trenches. The first drilling at Dugald River was undertaken by the Queensland Geological Survey during 1939. A predecessor to CRA purchased the acreage in 1948 and exploration and appraisal of the prospect continued spasmodically until the present (Sheppard and Main, 1990).

The Mount Isa ore body was found by a prospector who chanced on its gossanous outcrop in 1923. Mining began in 1927, but exploration did not begin until the late 1940s and even then it was focused within 20 km of the mine. Detailed surface mapping of ferruginous outcrops was the main exploration technique. A gossan was identified at nearby Hilton, but initial follow-up work failed to locate an ore body.

During the 1950s the concept of syngenetic ore formation gained acceptance and the search extended to other areas where the Mount Isa host sediments or their equivalents were thought to occur. Emphasis was placed on regional mapping and geochemical prospecting (Edwards and Atkinson, 1986). The chance collection of a hand specimen of gossan while soil sampling lead to the discovery of the Pb-Zn mineralisation at McArthur River (HYC ore body). This was probably the first major discovery of Pb-Zn in Australia consequent on exploration being directed at a specific geological environment at a site well removed from significant mining operations (Legge and Haslam, 1990).

Better metal prices during the mid to late 1960s and the ability to core to the required depths led to a reappraisal of the Hilton area. The use of a syngenetic model and correlation using tuff marker beds ultimately resulted in the discovery of an economic Pb-Zn-Ag ore body (Clark, 1975; B. V. Mathias pers. comm., 1993).

The Lady Loretta ore body was the next to be found, even if it was conceptionally unintentional. Given that both soil geochemistry and IP played a part, it can be argued that it was the first Queensland SSHBM ore body found by a combination of "modern" methods. Certainly, its discovery resulted in an increased use of these techniques, especially over other areas of Lady Loretta Formation. During the early to mid 1980s, the Lady Loretta Formation was explored for SSHBMs by several companies including overseas-based multinationals such as Shell, Getty and Amoco Minerals (Moeller, 1982; B. H. Jones, 1984; Watt, 1983; respectively). It was also considered a target for epigenetic silica-dolomite hosted copper.

During 1989, a major Pb-Zn-Ag ore body was (re)discovered by CRA near a small gossanous outcrop and discordant lodes that had been worked by prospectors just over a century before. Century, as it was named, has been plagued by unsuccessful negotiations with traditional landholders and large-scale mining has been deferred.

Other recent discoveries include the Walford Creek and Grevillea prospects. Current exploration relies heavily on EM, both ground and airborne, and on surface geochemical sampling (these techniques are discussed in Section 14.4).

14.2 PREVIOUS EXPLORATION MODELS BASED ON THE LADY LORETTA ORE BODY

The exploration model used by Berg (1986) and Beeson *et al.* (1989) was no doubt inspired by the then-current genetic models for HYC, Lady Loretta and Mount Isa. Their initial model can be summarised as:

- a graben setting
- restricted sedimentation in a discrete sub-basin
- thick carbonaceous shale sequence with thin cyclic clastic beds
- tuffaceous interbeds
- sedimentary breccias adjacent to a fault
- early synclinal structure
- host rocks overlain by a silty to sandy graded turbidite sequence
- abundant early pyrite
- presence of siderite.

Application of this model to the Lady Loretta Formation focused attention in the Mellish Park and Carrier areas. Beeson *et al.* (1989) subsequently incorporated lithogeochemistry into their exploration model by relating alkali enrichment (based on K:Al and K:Rb) to saline, shallow-emergent conditions of deposition considered favourable for mineralisation.

14.3 A NEW EXPLORATION MODEL

The first implication of many of the new genetic models is that exploration in the Lady Loretta Formation does not have to focus on finding lithostratigraphic and chronostratigraphic equivalents of the Ore Sequence. Lithostratigraphy, sedimentology and sequence stratigraphy all predict that host sediments similar to Lady Loretta will occur elsewhere in the Lady Loretta Formation and should also exist in a number of other formations in the McNamara Group. Analogies have already been drawn with the lower Gunpowder Formation, Paradise Creek Formation and parts of the Riversleigh Siltstone in numerous unpublished company reports (*e.g.* Derrick, 1993). Shales in the Esperanza Formation should not be overlooked. All these formations could be pursued as potential target sequences and the identification of suitable host facies is, to some extent, independent of the genetic model, since almost all deposits occur in highly carbonaceous and pyritic host rocks.

There are, however, several caveats introduced by the bias toward one or another depositional or mineralisation model. For example, if the conclusion of the current study is correct and the host rocks to the Lady Loretta mineralisation are lagoonal, their distribution would be much more patchy than as was envisaged when they were interpreted as a deep water shale.

14.4 EXPLORATION TECHNIQUES

14.4.1 Geophysical Methods

The Lady Loretta ore body has been used to test the effectiveness of various geophysical techniques including aeromagnetics, ground and airborne radiometric surveys, electrical surveys (IP, resistivity, SP), ground and airborne EM (EM-INPUT, SIROTEM, Scintrex MIP/EM, Crone transient EM, RMIP, QUESTEM) and ground-based gravity. Details are given in Amade (1986), Anderson *et al.* (1993), Lemcke (1986) and Rennie and Loudon (1973). Most of these techniques failed to unambiguously detect the mineralisation at depth. The later generation of airborne EM mapped facies within the Esperanza Formation as a conductor locally and was able to detect some character in rocks laterally equivalent to the Lady Loretta mine stratigraphy beneath Cambrian cover (Anderson *et al.*, 1993). It does not (in the opinion of the author) convincingly show the ore body.

Detailed gravity studies by Duffet (1996) detected the Lady Loretta mineralisation as a relatively small high of about 1 mgal amplitude over the centre of the Small Syncline. He believed that, despite the large vertical aspect ratio of ore and barite in the limbs of the Small Syncline, the massive pyrite accompanying the ore was probably the main contributor to the gravity anomaly.

14.4.2 Geochemical Surveys

The use of geochemical surveys in the search for northern Australian SSHBM ore bodies is discussed in Edwards and Atkinson (1986). The discovery of the Lady Loretta ore body is both a testament to the success of this technique and a useful test-case.

Soil Geochemistry

Soil geochemistry has been the most widely used geochemical technique in northern Australia and its success was vindicated by the discovery of the Lady Loretta ore body. The soils in the vicinity of the mine are lithosols with subordinate solodic soil (Cox and Curtis, 1977). Lead and Ag are the best indicators of mineralisation at depth. Zinc, because of its greater mobility and the effects of lateritisation, tends to halo the Ore Sequence. Zinc values are also conspicuously higher in areas of low topographic relief (Cox and Curtis, 1977). Other elements such as Hg and Th might be useful pathfinders (see Section 4.10) particularly in lithosols.

Rock Chip Sampling

The majority of known SSHBM ore bodies (Lady Loretta, Mount Isa, Hilton, HYC, Grevillea) are characterised by gossanous outcrop and surface-rock chip sampling was a reliable indicator of subsurface mineralisation. Century also has a gossanous surface expression, but the relationship to Proterozoic-hosted mineralisation is more problematic. Furthermore, numerous other instances of "gossans" in the north Australian Proterozoic rocks have been drilled without identifying base metals at depth.

The best approach to the analysis of rock chip geochemistry is to use direct detection of target metals in conjunction with the suite of multi-element indices developed by Large and McGoldrick (1993). Individual pathfinder elements such as Ba, Cd, Hg and Th might also be useful.

As discussed in Appendix A-8, unusual carbonate chemistries such as siderite, ankerite and Mg/Mn carbonates are not restricted to the ore body and should not be used, in isolation, as a vector to mineralisation in the Lady Loretta Formation. Rock chip analyses from argillaceous rocks are more reliable indicators of mineralisation than carbonates. RAB drilling may be necessary since the shales are usually recessive and weathering is commonly relatively deep.

The geochemistry of the basal breccia to the Lady Loretta Formation may be misleading in any rock chip sampling survey (see Section 12.5).

Stream Sediment Sampling

There are few documented examples of stream sediments having been successfully used to identify base metal mineralisation in northern Australia and such studies conducted in the vicinity of known ore bodies can be difficult to interpret. Some success has been claimed using the silt-sized fraction (<80 mesh) at Dugald River for the direct detection of metals (Edwards and Atkinson, 1986). The discovery of the mineralisation at Grevillea has been reported as having been based on stream sediment sampling (Jenkins, pers. comm., 1996).

Stream sediment sampling for Cu has been used, with mixed success, in the vicinity of the Lady Annie prospects (there are now problems of contamination due to drainage from old workings) but these surveys were inferior to rock chip sampling and were of little use in detecting the Zn-Pb-Ag mineralisation at Lady Loretta.

Pb Isotopes

Gulson and Mizon (1979) claimed that lead isotopic studies of gossans can distinguish between those overlying stratiform Cu-Pb-Zn mineralisation and those developed on barren ferruginous rocks. Vaasjoki and Gulson (1985) advocated this technique at Lady Loretta. Several exploration companies currently use Pb isotope model ages to discriminate trace Palaeoproterozoic mineralisation from younger epigenetic Pb that, presumably, is less likely to be prospective.

14.5 SUMMARY AND DISCUSSION

The majority of SSHBM ore bodies in the north Australian zinc belt were found because of their gossanous outcrop and/or surface geochemical expression. Empirical exploration techniques using geophysical methods and surface and downhole geochemistry can be extended to the search for blind ore bodies. The Lady Loretta example indicates that a suite of alteration indices and some individual pathfinder elements should be used. Exploration need not be focused on lithostratigraphic equivalents of the Lady Loretta Ore Sequence but can be directed toward other highly carbonaceous and pyritic facies. The distribution of these potential host rocks should be predictable using geophysics, sedimentology and sequence stratigraphy.

Chapter 15 - Synthesis

15. SYNTHESIS - GEOLOGICAL HISTORY OF THE LADY LORETTA FORMATION

15.1 REGIONAL DEPOSITIONAL MODEL

15.1.1 The Tectono-Sedimentary Setting

Several previous tectono-sedimentary models for the Lady Loretta Formation proposed a rift setting (*e.g.* Dunnet, 1976). These ranged from a basin-wide scale feature, through a rift several tens of kilometres wide, to an isolated half-graben in the vicinity of the present Lady Loretta mine. Lithofacies mapping and correlation undertaken during the present study found no evidence to support any of these propositions (Dunster and McConachie, in press)*. The Lady Loretta Formation, like several other formations in the same group of the Mount Isa Basin (McConachie *et al.*, 1993), is interpreted to have been deposited on a broad carbonate platform that was more argillaceous and, overall, possibly deeper to the southeast. A rim, produced by high-relief microbialites, probably developed but it was spatially and temporally restricted compared to that proposed by Sami *et al.* (1997) for the deposition of the underlying Esperanza Formation.

Much of the outcrop of the lower Lady Loretta Formation is a ferruginous chert breccia and this had previously been interpreted as evidence of regional uplift and intraformational subaerial exposure. The present study interprets the "basal breccia" as a duricrust because it does not continue into the subsurface, the apparent large thickness variations are not consistent with a sedimentary origin, it transgresses stratigraphy regionally and locally and the petrography of the breccia and the jigsaw fit of clasts are similar to a silcrete. Although the timing of duricrust formation is not well constrained, it postdates the major tectonism that affected the Palaeoproterozoic rocks and so has no relevance to a sedimentary interpretation of the Lady Loretta Formation.

15.1.2 Regional Sedimentary Model

The regional sedimentary model proposed for the Lady Loretta Formation consists of facies ranging from sub-wavebase to sabkha. These were deposited during a series of fluctuations in relative sealevel that constitute an overall regression from the sub-wavebase high-relief microbialites of the Esperanza Formation to the shallow marine and fluvial sandstones of the Shady Bore Quartzite.

Within the Lady Loretta Formation, shale, laminated to massive argillaceous dolostone and fine grained sandstone containing hummocky and swaley cross-stratification are interpreted as the deepest-water facies.

Shallow marine carbonates now consist of variably silicified dolostone and include microbialites that range form prone laminites to bioherms and biostromes of domal, digitate, pillared, cuspate, conical and columnar forms. The largest buildups had up to several metres of synoptic relief. They were flanked by debris aprons and cut by channels that are oriented both parallel with, and at right angles to, the dominant palaeocurrent directions.

The digitate and columnar microbialites are commonly elongate and/or inclined. These features are interpreted as local reefal build-ups developed in shallow water and subject to wave action.

Ooid and ooid/pisoid grainstones are common in the northern Lady Loretta Formation and also occur in the Upper Clastic Unit above the Lady Loretta ore body. Although they appear to occur repeatedly in the same lithostratigraphic interval, the ooid grainstones do not persist for any more than a few hundred metres along strike. The majority of the ooid grainstones are interpreted as small shoals developed in shallow agitated water. A grainstone from the western flanks of Kamarga Dome that contains "giant" ooids was studied in detail. The lack of spalling of the outer coat, the internal morphology of the cortex and the relatively low Sr content contrast markedly to other examples of "giant" ooids from the Neoproterozoic. On this basis, it is unlikely that the examples from the Lady Loretta Formation had an aragonite precursor, as proposed for other "giant" ooids.

Widespread carbonates and mixed carbonate/siliciclastics in the northern outcrops of the Lady Loretta Formation appear to be cyclic and developed as a facies mosaic. They are interpreted as peritidal on the basis of bipolar-bimodal palaeocurrent directions, flaser to lenticular bedded units, tidal rhythmites, interference wave ripples and herringbone cross-stratification with reactivation surfaces. Storm deposits such as imbricated plate breccias and gutter casts are also common. Widespread casts and moulds of halite and sulphate evaporite pseudomorphs of discoidal gypsum, enterolithic anhydrite and cauliflower cherts are interpreted as an evaporitic overprint produced during regression when a marine sabkha developed locally. Associated shallow water sedimentary features include desiccation cracks, synaeresis cracks, washout rills, scour pits and wrinklemarks. Highly carbonaceous and pyritic shale and variably diagenetically altered Fe and Mn-rich dolomitic siltstone were deposited in isolated areas laterally and stratigraphically associated with tidal and possible subaerial facies. These pyritic facies occur at several localities in the Lady Loretta Formation. The Lady Loretta ore body, consisting of 8.3 Mt of Zn-Pb-Ag, is hosted by such facies.

15.2 DEPOSITIONAL MODEL FOR THE VICINITY OF THE LADY LORETTA MINE AND EARLY MINERALISATION MODELS

15.2.1 SYN-SEDIMENTARY FAULT ACTIVITY ON THE CARLTON FAULT ZONE

Prior to this study, most workers (*e.g.* Amade, 1986; Carr, 1981) considered that the Carlton Fault Zone to the north northwest of the mine was active during the deposition of the ore host rocks. The fault scarp was interpreted to have shed the inter-ore breccias and to have been the source of turbidites. However, the present study disputes the interpretation of syn-sedimentary fault activity on the Carlton Fault Zone. None of the units in the mine stratigraphy thicken toward the fault or show any facies changes that might be expected adjacent to an active fault. A more rigorous sedimentological study of the inter-ore breccias and measurement of hundreds of palaeocurrent directions do not support an active fault model (Dunster, 1996)*. Furthermore, the mine stratigraphy can be correlated to the Tom Cat area well away from the mine and across the Carlton Fault Zone. Several workers (*e.g.* Carr, 1981; Large 1980, 1983) who advocated a classic SEDEX mineralisation model also suggested that the fault zone was the conduit for mineralising fluids.. However, there is no textural evidence to support this. There are no systematic variations in the Cu, Ag or Zn tenor, overall ore grade or ore thickness toward the fault.

15.2.2 DEPOSITION AND A MODEL FOR EARLY MINERALISATION

The deposition of the upper-most Esperanza Formation in the vicinity of the present Lady Loretta mine was characterised by high-relief microbialites that probably constituted a barrier complex. Some local variation in the morphology of the microbialites was noted during the present study. Whereas, typical high-relief forms are abundant in the Esperanza Formation to the east of the mine and immediately north of the Carlton Fault Zone, these forms are less abundant in the Greater Loretta Syncline, and to the west. This may indicate shallower conditions in the vicinity of the mine at this time.

Initial deposition of the Lady Loretta Formation is marked by the rapid demise of the distinctive Esperanza Formation microbialites. The sparse outcrop indicates a local variation in the basal Lady Loretta Formation. Laminated to thin bedded silicified dolostone and subordinate fine grained sandstone with tidal bedding occur to the southeast of the ore body and ferruginous and argillaceous lithologies occur to the north of the Carlton Fault Zone. It is unclear whether these lithologies and their sedimentary features should be interpreted as having been deposited during a major transgression or regression.

There is little outcrop and no drillhole intersections of the overlying *ca.* 200 m of stratigraphy. The scant data indicate laminated silty and argillaceous sediments interbedded with fine grained sandstone with lensoidal and flaser bedding and bimodal bipolar palaeocurrent directions. These are interpreted as a peritidal complex.

The lowest unit recognised in the mine stratigraphy is the Lower Carbonate Unit. It consists of thinly bedded to laminated, variably dolomitic siltstone, claystone and carbonaceous shale with subordinate dolostone and sandstone. This unit is characterised by parallel lamination; but sporadic wave ripples with opposed palaeocurrent directions consistent with the formation regionally, low angle trough crossbeds, flaser and lensoidal bedding and synaeresis cracks are present. They can be interpreted as a tidal influence in an overall quiet shallow water environment.

The overlying Pyritic Unit includes the X to XI interval (defined in Section 10.3.4) immediately underlying the Ore Sequence and contains locally abundant bedded pyrite interpreted as microbial mat, pyritised and silicified domal and cumulate microbialites and subordinate highly carbonaceous shale beds interpreted to have formed from settled detrital organic matter. The carbonates in this interval were in equilibrium with water containing isotopically light oxygen. Displacive euhedral gypsum pseudomorphs and desiccation cracks occur peripheral to the ore body. This interval is interpreted as the first evidence of a restricted water body with prolific microbial growth. The edges of the water body were periodically subaerially exposed and a sulphate evaporite overprint developed locally.

A reconstruction of the XI to XII interval, corresponding to the deposition of the host rocks of the Ore Sequence and the Ore Sequence Equivalent, is shown in Figure 10-6. The unmineralised host rocks now consist of bedded pyrite, highly carbonaceous shale and diagenetically altered Fe- and Mn-enriched dolomitic siltstones and dolomites and minor "tuff" and breccia. Some of the argillaceous and carbonate lithologies are rhythmically bedded and resemble tidalites. Few of the so-called inter-ore breccias are true sedimentary breccias. They are less than 40 cm thick and cannot be correlated laterally for more than a few tens of metres despite good drilling control. Distinctive pink feldspar-chert beds in the Ore Sequence have been referred to as "tuffs" although not all such beds necessarily had a volcanic component. Microbial fabrics, including extensive prone mat and several digitate forms, and thin beds of acicular gypsum crystal pseudomorphs and moulds can be traced over the eastern limb of the Small Syncline. Deposition is interpreted to have occurred in a lagoon developed on the tidal flat. Red-bed siltstones with a strong evaporite overprint, to the west of the present mine, may have formed on a sabkha.

One genetic model for the Lady Loretta mineralisation (McGoldrick *et al.*, 1996)* invoked syn-sedimentary movement of low temperature (< 100°C) moderately oxidised groundwaters laterally and vertically through the unconsolidated sediments. The migrating fluid had a heavier isotopic signature than the connate pore waters that it displaced. Microbial growth was stimulated by the discharging fluid. The barite that flanks the ore body may have been deposited as the fluid mixed with bottom waters and/or reacted with sulphate evaporites. As the discharging fluid became hotter (100°-120°C) and more oxidised, it brought in significant quantities of Zn and Pb, but much less Ba and Fe. Some metal sulphides accumulated as syngenetic beds on the lagoon floor, but considerable quantities were probably precipitated in the shallow subsurface anoxic sediments. Abundant microbial and syndiagenetic pyrite continued to form as the mineralising system waned (McGoldrick *et al.*, 1996)*.

The aptly named *ca.* 100 m thick Cyclic Unit that occurs above horizon XII, is characterised by non-random sedimentation at a centimetre to decimetre-scale and can be interpreted as the steady state formation of microbial mat and carbonate deposition repeatedly punctuated by influxes of sandy and silty sediment. Each pulse of introduced sediment is characterised by clasts of ripped-up microbial mat and soft sediment deformation such as convolute bedding and small scale slumps. Intervals of soft sediment deformation between the XII and XIII horizons are attributed to fluid injection and can be correlated between drillholes in both synclines and to the Tom Cat area. The return to ambient carbonate precipitation was accompanied by an increasing rain of carbonaceous matter derived from microbes in the water column. Eventually, microbial mats were re-established and the next cycle begins (Carr, 1981; this study). Although the precise water depth and sedimentary setting are ambiguous, the literally thousands of cycles may suggest a tidal, seasonal or storm influence.

The XVII horizon, about 90 m above the top of the Ore Sequence is interpreted as a maximum flooding surface. Above that, an overall regression is interpreted up to a sequence stratigraphic boundary at XXII. The lithologies, including ooid grainstones and sandstones with halite pseudomorphs, above this level are interpreted to represent a change to a shallow, moderately high energy marine setting. This is probably the start of the transition to the overlying Shady Bore Quartzite.

15.3 DIAGENESIS AND LATE EPIGENETIC MINERALISATION MODELS

The carbonates in the Lady Loretta Formation have a complex diagenetic history, interpreted to include regional dolomitisation, pressure solution and at least incipient silicification. At several locations, including the Lady Loretta mine, highly carbonaceous and pyritic shales are associated with Fe and Mn enriched carbonates. These are interpreted to be a product of normal diagenesis and are not hydrothermal as was previously proposed. Many of the highly carbonaceous lithologies would have acted as petroleum source rocks during burial. The hydrocarbons generated are preserved as bitumen in the vicinity of the Lady Loretta mine. Bitumen was also generated by the radioactive maturation of organic matter.

The close association between hydrocarbons and SSHBM mineralisation has been noted at Century and forms an intrinsic part of the late epigenetic mineralisation model proposed by Broadbent *et al.* (1996). McConachie and Dunster (1996)* also advocated a petroleum-style late epigenetic model for base-metal mineralisation in the northern Mount Isa Basin. Both these models could be applied to the Lady Loretta ore body.

The syntectonic and/or syn-metamorphic models favoured for the Mount Isa ore body (*e.g.* Perkins, 1990; Bell and Hickey, 1996) have also been proposed for Lady Loretta. However, the timing of epigenetic mineralisation at Lady Loretta is unlikely to be the same as advocated at Mount Isa. What is believed to be the same folding event has clearly deformed, remobilised and recrystallised much of the sulphide and sulphate mineralisation at Lady Loretta (McGoldrick *et al.*, 1995).

Late epigenetic models are supported by the difference in age between the SHRIMP zircon date of the host sediments (1647±4 Ma) and the Pb model age from the ore (within range of 1600 -1570 Ma). One of the major problems with any late replacement model for SSHBM ore bodies in general, and Lady Loretta in particular, is the formation of literally thousands of concordant internally-layered bands of mineralisation without any significant contemporaneous cross-cutting relationships. This is difficult to explain in what should have been consolidated argillaceous rocks with little remnant porosity and permeability.

Chapter 16 - Philosophical Reflections

16. PHILOSOPHICAL REFLECTIONS

16.1 THOUGHTS ON STUDIES OF AUSTRALIAN SSHBM ORE BODIES

Studies of Australian SSHBM ore bodies and their host rocks have been hindered by a number of factors that are presented below:

- **Failure to Recognise the Sedimentary Origins through the Metamorphic Camouflage**

The notion that the metamorphic rocks of the Mount Isa "Inlier" pre-dated the sedimentary rocks of the "Lawn Hill Platform" led many early studies to conclude that mineralisation in the two terrains was different. The fact that there is probably a continuum of increasing metamorphic grade and that the host rocks were originally sediments of the same age (rendering the term "Inlier" inappropriate) still escapes some people.

Early studies of the Mount Isa / Hilton and Broken Hill ore bodies regarded them as examples of syn-metamorphic mineralisation. There are vocal proponents of "syn-D2.5" or "syn-D3" mineralisation (which may, or may not, be the same as syn-metamorphic) and those who recognise an entire class of ore-deposits called the "metamorphic-hosted Broken Hill-type deposit". King (1975) referred to this as "Stanton's metamorphic camouflage"; a sentiment echoed by McConachie (1993b) amongst others. Seminal work on the Broken Hill ore body (Wright *et al.*, 1993) recognised sedimentary facies control on the mineralisation despite the metamorphic camouflage and Webster (1996) suggested the possiblity of syngenetic biogenic metal accumulation. Did ore genesis pre-date metamorphism at Mount Isa and Broken Hill? Are the genetic models for these ore bodies preoccupied with the structural and metamorphic overprint?

- **Difficulties in Interpreting the Sedimentology of Proterozoic Host Sequences**

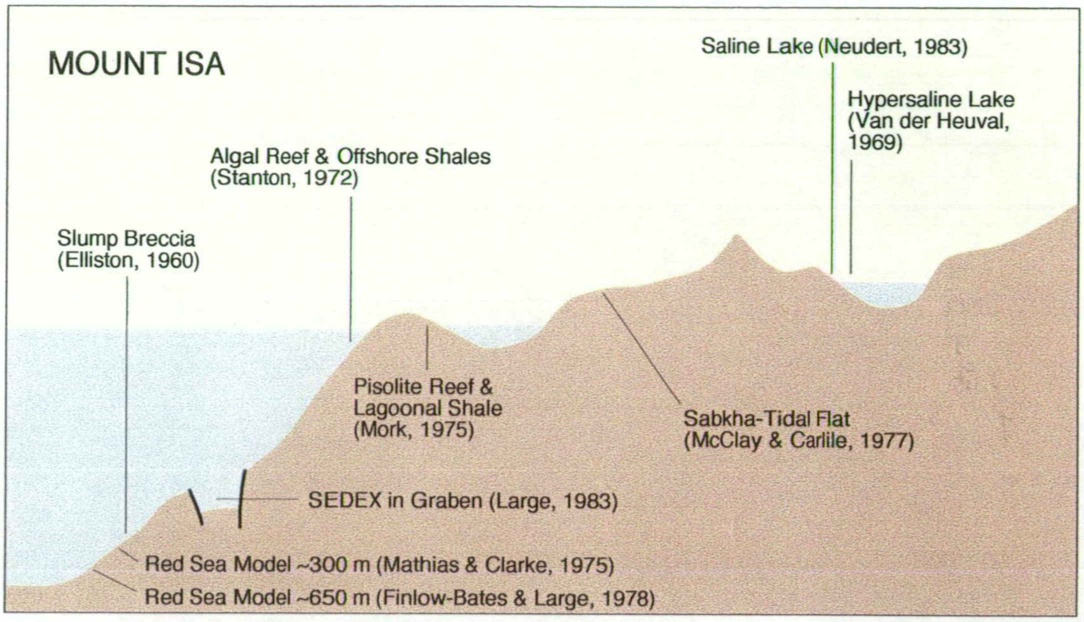
Sedimentologists have had great difficulty in working with the host rocks to Australia's SSHBM ore bodies. Interpretations of the environment of deposition for the McArthur River and Mount Isa host sediments have varied from sabkha or lacustrine to anoxic deep marine. The various interpretations for the environments of deposition of SSHBM host rocks are shown diagrammatically in Figure 16-1 and, in many instances, were influenced by the then-current genetic model for mineralisation (see next point).

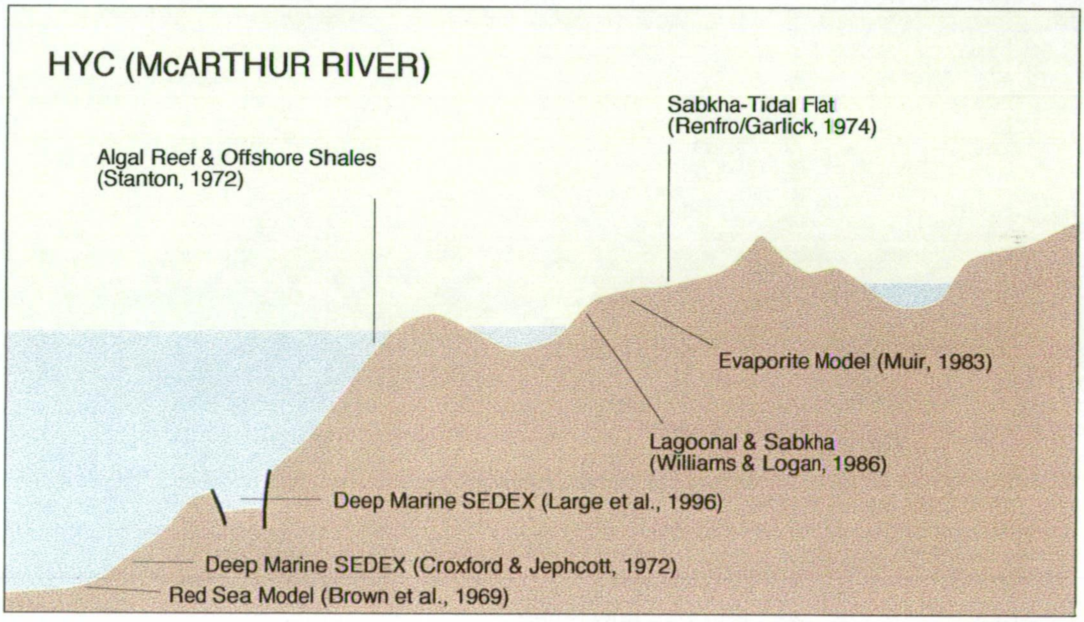
The current study of the Lady Loretta host-rocks is not model-driven and it is the best possible interpretation based on the available data and the current interpretations of analogues. This must be seen in the light of on-going debate on numerous themes, *e.g.* the interpretation of laminated sedimentary rocks, crusts, hardgrounds, evaporite pseudomorphs and the significance of accommodation space and carbonate deposition with reference to metre-scale shallowing-up cycles, auto- and allocyclic mechanisms, the worth of Fischer plots and whether bed thickness is a reflection of accommodation space.

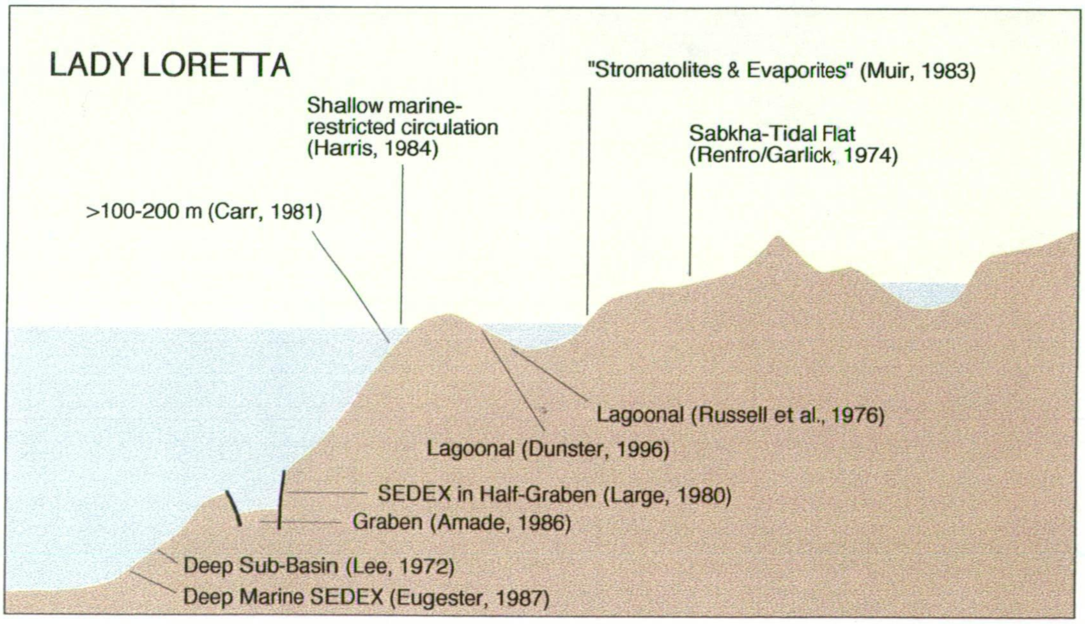
- **A Preconceived Genetic Model of Mineralisation**

At best, models of mineralisation have varied according to the postulated environment of deposition of the host sediments. At worst; and as is too often the case; an ore body is shoe-

Figure 16-1: A cartoon showing the various sedimentary environments interpreted for the host rocks of SSHBM ore bodies. References not given in this thesis can be found in Large et al. (1996), Logan (1979) and Neudert (1983).


MOUNT ISA
Saline Lake (Neudert, 1983)
Hypersaline Lake (Van der Heuval, 1969)
Algal Reef & Offshore Shales (Stanton, 1972)
Slump Breccia (Elliston, 1960)
Pisolite Reef & Lagoonal Shale (Mork, 1975)
Sabkha-Tidal Flat (McClay & Carlile, 1977)
SEDEX in Graben (Large, 1983)
Red Sea Model ~300 m (Mathias & Clarke, 1975)
Red Sea Model ~650 m (Finlow-Bates & Large, 1978)


HYC (McARTHUR RIVER)
Sabkha-Tidal Flat (Renfro/Garlick, 1974)
Algal Reef & Offshore Shales (Stanton, 1972)
Evaporite Model (Muir, 1983)
Lagoonal & Sabkha (Williams & Logan, 1986)
Deep Marine SEDEX (Large et al., 1996)
Deep Marine SEDEX (Croxford & Jephcott, 1972)
Red Sea Model (Brown et al., 1969)


LADY LORETTA
"Stromatolites & Evaporites" (Muir, 1983)
Shallow marine-restricted circulation (Harris, 1984)
Sabkha-Tidal Flat (Renfro/Garlick, 1974)
>100-200 m (Carr, 1981)
Lagoonal (Russell et al., 1976)
Lagoonal (Dunster, 1996)
SEDEX in Half-Graben (Large, 1980)
Graben (Amade, 1986)
Deep Sub-Basin (Lee, 1972)
Deep Marine SEDEX (Eugester, 1987)

horned into a preferred mineralisation model and the sedimentology is biased by that preconception. The Lady Loretta ore body was deemed to be a SEDEX deposit without any evidence of boiling; therefore the host sediments *must* have been deposited in deep water. This preconception led to a preoccupation with syn-sedimentary grabens, deep-water turbidites and exhalative siderite, barite and chert.

- **The Assumption that the Same Genetic Model can be Applied to All SSHBM Ore Bodies**

Unfortunately, the search for a grand unified theory for the origin of SSHBM ore bodies has led to the dogmatic rejection of the concept of the multiple working hypothesis. Attempts to assign a common environment of deposition and tectono-sedimentary setting to all these ore bodies are fraught with peril. In the case of the Lady Loretta ore body, all the baggage marked "Mount Isa Inlier" was sent from Mount Isa to its smaller northern cousin. This led to a preoccupation with finding similarities with the Mount Isa ore body and the blind adoption of the same sedimentary and genetic model.

- **Fashions and Cliques in Genetic Models**

Genetic models are the yoyos and hula-hoops of economic geology. Witness the repeated alternations between epigenetic and syngenetic models for the Mount Isa, HYC and Broken Hill ore bodies.

To some extent, the various genetic models proposed for SSHBM ore bodies reflect the three-fold classification of rocks and the corresponding specialised disciplines, and proponents are commonly associated with one or other academic faculty, company or mine.

The SEDEX "vulcanologists" borrow from VHMS ore bodies and would have hydrothermal ore-bearing fluids exhaling onto the seafloor to deposit the ore at the sediment/water interface. The siderite, barite and chert at Lady Loretta mine have all been interpreted as hydrothermal exhalites that accompanied mineralisation. This school of thought favours volcanics as the source of the metals and igneous melts as heat engines for fluid circulation. Igneous heat engines, mantle-tapping faults and deep-seated circulation cells have also been advocated in an analogy with models for porphyry Cu mineralisation.

The McGoldrick *et al.* (1996) model for the Lady Loretta deposit stresses the sedimentary aspects and favours early epigenetic replacement. Those who advocate petroleum-style mineralisation models see similarities with the dewatering of basinal shales, long distance migration and late epigenetic replacement as applied to MVT genetic models. Broadbent *et al.* (1996), in effect, described the Century ore body as a mineralised oil reservoir. Purists of this school would see the ore-forming process as part of the normal evolution of a sedimentary basin (as argued by Fontbote, 1981 and McConachie, 1993b).

The proponents of "syn-D3" late epigenetic replacement are commonly structural geologists or metamorphic petrologists and naturally stress these aspects, usually with migration of the mineralising fluid along fault feeders. The concept of fluid movement along faults advocated for metal deposits is almost always a simple fluid-feeder active late in the basin history and little thought is given to maintaining the conduit as the mineralising fluids pass. This contrasts with the situation in the petroleum industry where late faults are variously interpreted as seals to lateral migration or fractures breaching a petroleum trap.

16.2 THE FINAL WORD - THIS IS NOT THE FINAL WORD

The final words in this thesis are an attempt to put the Ph in PhD and rightfully belong to the philosophers:

"Geology does not generally admit of a mathematical demonstration of its conclusions. They rest upon the balance of probabilities. But this balance is liable to alteration as facts accumulate or are better understood" (Geikie, 1905).

"It is not in accord with the nature of scientific research to maintain the belief in possessing the only correct theory, but rather to gradually approach closer to the truth by doubting all theories" (Jung, 1954).

Chapter 17 - References

17. REFERENCES

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